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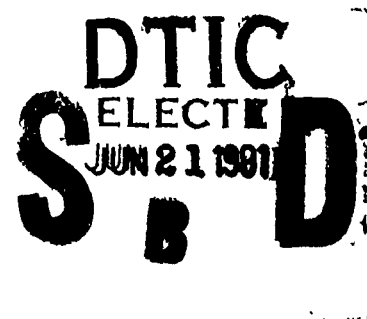
Key Issues in the Application of Existing Conventional High Speed Railroad Technologies to Mobilization

by
Donald E. Plotkin

The development of high speed passenger service (at or above 125 mph) has stimulated questions about the adoption of similar technology for Army mobilization and heavy freight traffic. This report identifies key issues involved in the application of high speed railroad technology to mobilization. Topics considered include: route alignment and track requirements, equipment (locomotive and car) design, power and energy needs, construction and maintenance costs, operational and safety issues, and general technological challenges.

This report compares characteristics of high speed and existing conventional services and discusses the differing requirements for heavy freight and passenger transport. Also included are performance comparisons between a high speed French TGV-SE passenger train and an idealized (hypothetical) TGV-style freight intended to carry M1 tanks.

Hauling heavy freight at high speed presents substantial technical and economic challenges. The practical use of high speed trains for mobilization implies the need for a basic national high speed railroad network, much of which would require new construction. Thus, the considerable costs associated with high speed would have to be carefully weighed against the expected benefits.



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FOREWORD

This study was conducted for the Directorate of Military Programs, Headquarters, U.S. Army Corps of Engineers (HQUSACE) under Intra-Army Order No. CRREL 89-102, "Assessment of High Speed Rail Transportation." The HQUSACE technical monitor was Paige Johnson, CEMP-ET.

This work was performed by the Engineering and Materials Division (EM) of the U.S. Army Construction Engineering Research Laboratory (USACERL). The principal investigator was Donald E. Plotkin. Dr. Paul A. Howdysshell is Chief, EM. The USACERL technical editor was Gordon L. Cohen, Information Management Office.

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COL Everett R. Thomas is Commander and Director of USACERL. Dr. L.R. Shaffer is Technical Director.

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KEY ISSUES IN THE APPLICATION OF EXISTING CONVENTIONAL HIGH SPEED RAILROAD TECHNOLOGIES TO MOBILIZATION

1 INTRODUCTION

Background

Most recent developments in high speed railroad operations have occurred outside the United States, most notably in France, Japan, and Germany. As high speed railroad technology has evolved, the differences between those latest advances and U.S. operations have become more evident, and the desire to emulate European and Japanese technologies has increased. In addition to their general commercial service, the high speed systems have also appeared potentially attractive for Army mobilization use.

Objective

The objective of this work is to identify and discuss key issues related to, and their potential effects on, the application of existing conventional high speed railroad technology to support Army mobilization.

Approach

To assess the potential for application of high speed railroad systems to support Army mobilization, the following general issues were examined:

1. The general characteristics of conventional high speed railroad systems now operating or under construction
2. The technological demands imposed by the application of high speed railroad technology to Army mobilization, particularly in the area of transporting heavy freight
3. The route alignment and track requirements that would apply when adapting existing railroads to (or creating entirely new routes for) high speed freight and passenger service
4. Performance data from existing high speed systems and performance requirements for carrying heavy freight at high speed.
5. The costs and benefits of applying conventional high speed railroad technology to Army mobilization.

Documentation and analysis of these issues were accomplished through a study of the professional and industry literature and other available resources pertaining to (1) the published characteristics of existing high speed rail systems, (2) the general requirements of Army mobilization activities related to rail transportation, (3) the general requirements for high speed movement of heavy freight by rail, and (4) the characteristics of the existing U.S. railroad network.

Scope

The technologies covered in this report generally represent the most well known and successful existing conventional high speed railroad operations and equipment. "Existing" refers to those systems now in service or nearly ready for service—technologies beyond the experimental stage. "Conventional" refers to systems that run with steel wheels on steel rails for guidance and require wheel/rail adhesion for propulsion.

While the American Railway Engineering Association (AREA) commonly uses the term "high speed" in referring to operations at or above 150 mph,^{*} a lower limit of 125 mph is used in this report. The 125 mph limit is commonly found in the general literature (usually specified as at or above 200 km/hour). It also permits inclusion of systems used in the United States, and is the lower limit for high speed as defined by the American Society of Civil Engineers (ASCE).¹

Systems falling outside these definitions are mentioned where useful comparisons warrant their inclusion.

^{*} English units of measure are used throughout this report. A metric conversion table is published on page 52.

¹ R.L. Wayson and W. Bowlby, "Noise and Air Pollution of High Speed Rail Systems," *ASCE Journal of Transportation Engineering*, Vol 115, No 1 (January 1989)

2 EXISTING CONVENTIONAL HIGH SPEED SYSTEMS

This chapter will briefly describe selected existing conventional high speed railroad operations. This summary pertains to systems currently in service that have maximum speeds of at least 125 mph and use the conventional steel wheel-on-steel rail technology for guidance and propulsion.

New Trains for Existing Routes

Several trains have been designed to operate at faster speeds on existing routes or on routes with some track and alignment improvements. These trains are usually intended for a top speed of about 125 mph—the bottom end of the high speed classification. The ability to run on existing track at faster speeds is achieved through lightweight engine and car designs, a lowered center of gravity, improved suspension and brake systems, and often with the help of tilt-body features (discussed below).

These trains are generally one of two types: (1) locomotives hauling individual cars or (2) "trainsets" with a "power car" at each end and sets of semipermanently coupled cars in between. Equipment for trainsets is typically not compatible with other engines and cars.

The only U.S. operation currently included in the high speed category is in the Northeast Corridor from New York City to Washington, DC. In January 1969, electric multiple-unit (EMU) Metroliners began operation at speeds up to 130 mph. These cars had numerous electrical and mechanical difficulties and are no longer in service, but their successful car body design, suspension, and brake system were the model for Amtrak's Amfleet cars. New York-to-Washington trains are now locomotive-hauled (electric AEM-7s with Amfleet cars) and achieve about the same top speed.

In Canada, diesel-powered LRC (Light-Rapid-Comfortable) trains run between Montreal and Toronto at a top speed of 125 mph. These are intended to run as trainsets, with six regular cars plus a power car at each end. In Great Britain, another fleet of diesel-powered trainsets operates; this HST, or High Speed Train, runs at a top speed of 125 mph.

In Europe, trains that currently operate at top speeds of 125 mph are primarily locomotive-hauled with overhead electric power—similar to Amtrak's Northeast Corridor operation. Trains of this type operate in Germany, Italy, and France.

Tilt-Body Designs

These designs were developed primarily to allow faster operation on existing track, where curves are sharper than normally desired for high speed operation and where high speed trains share track with low speed trains. In either of these cases, high speed operation would require greater curve superelevation or more superelevation unbalance than passenger comfort or safety would allow (see *Curves and Superelevation* in Chapter 4).

By having the car body tilt inward on curves, trains can safely and comfortably travel faster than would otherwise be permitted. The inward tilt puts the car body more in line with the resultant of vertical

(gravitational) and horizontal (centrifugal) forces, thus the sensation of outward force is smaller and the overturning moment on the train is reduced.

There are two basic tilt-body designs: active and passive. In passive designs, the centrifugal forces due to any superelevation unbalance cause the car body to tilt until equilibrium is reached. The advantage of this design is that, within the limits of rotation, the proper amount of tilt is automatically applied regardless of speed, curvature, or actual superelevation. However, since the mass of the car body is relatively great, there is a time delay before the car body moves into its equilibrium position. This delay can result in rough entry and exit from curves, as was the case with United Aircraft's TurboTrains, which ran from New York to Boston from 1969 to 1976.²

With active tilt designs, sensing equipment in the car controls a pneumatic or hydraulic system that quickly applies the appropriate amount of tilt to the car body. In this way, the car body can be made to adjust to superelevation without the inherent delays of the passive system. However, this power-tilt feature presents a difficult challenge to designers. It adds to the complexity and expense of trainsets in both construction and maintenance, and can create a potential comfort and safety problem if the system fails to operate correctly. The first power-tilt system was built into Great Britain's APT (Advanced Passenger Train), which had problems with its power-tilt system from its inception in 1972 until its retirement in 1986.³

An improved active tilt design is incorporated into trains which began service in Sweden on September 4, 1990. To further improve operation around curves (and reduce rail and wheel wear) these trains are equipped with self-steering trucks. In this design, both axles in the truck are automatically re-aligned to an improved orientation which better accommodates curvature in the track.⁴ An illustration of this concept is shown in Figure 1.

New High Speed Systems

The true new-generation passenger railroad systems are all characterized by completely new routes, new equipment, and new support facilities—all designed to operate as an integral system. Such systems now operate in Japan and France, with German operations scheduled to begin in 1991.⁵

The first of these systems was Japan's Tokaido line, which began service on 1 October 1964⁶ on its new 320-mile route from Tokyo to Osaka. There are now four Shinkansen (bullet train) lines in operation, with maximum allowable speeds from 137 mph on the oldest (Tokaido) line to 170 mph on the newest (Joetsu). New trains being developed for these lines could permit a maximum speed of 186 mph.⁷

² Eric H. Sjökvist, "Worldwide Development of Propulsion System for High speed Trains," *Transportation Research Record*, No. 1177 (Transportation Research Board, 1988), p 64; T. Nelligan and S. Hartley, *Trains of the Northeast Corridor* (Quadrant Press, 1982), p 74.

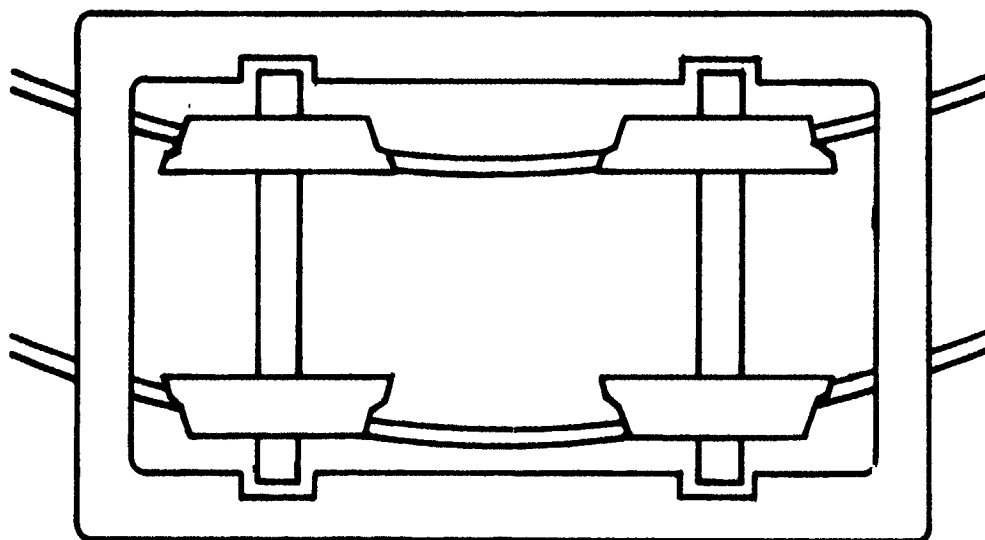
³ Eric H. Sjökvist, pp 60,62.

⁴ "Tilting Train is SJ's Survival Tool," *International Railway Journal* (April 1990).

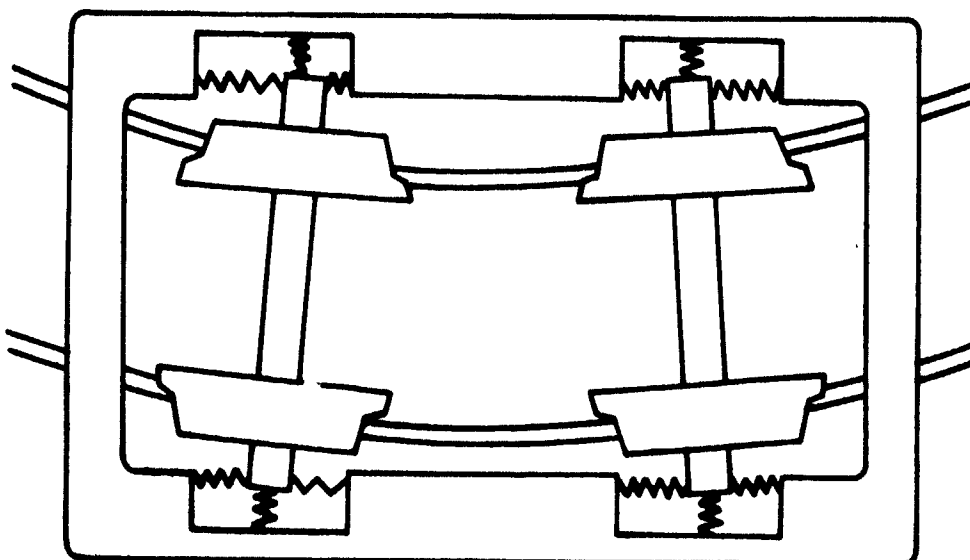
⁵ T. Rahn and W. Spohrer, "Development of New High-Speed Motor Train Units to be Operated on the German Federal Railway Network," *Proceedings of the Institution of Mechanical Engineers*, Vol 202, No. D2 (Institution of Mechanical Engineers, 1988), p 135.

⁶ S. Takahara and Y. Sato, "Recent Practices of Track Management on the Shinkansen," *Japanese Railway Engineering*, Vol 23, No. 3 (1983), p 2.

⁷ Eric H. Sjökvist, p 71.



a. Conventional Truck



b. Steering Truck

Figure 1. Steering truck concept. (Source: *High Speed Transportation: The Swedish Approach*, corporate publication (Asea Brown Boveri, undated), p 8.

Currently, the fastest high speed lines are those of the TGV (Trains à Grande Vitesse, or High Speed Trains) in France. The Southeast (SE) line began operation in 1981, with a top speed of 168 mph. The Atlantic line, which began operation in 1989, permits a top speed of 187 mph.⁸

The new German ICE (Inter-City Express), scheduled to begin service in 1991, will run on a combination of new and upgraded routes. Top speed will be 155 mph on new routes and 125 mph on upgraded lines.⁹

In recent years, France and Germany have been competing for the world speed record for a steel wheel-on-steel rail system. These records have been set with shortened and modified versions of high speed equipment intended for revenue service. A summary of this information is shown in Table 1.

Routes and Roadway

The newly constructed routes are the real key to the significantly reduced trip times possible for high speed operations. With new routes, not only are higher maximum speeds attainable, but the percentage of route mileage on which maximum speed may be run is greatly increased. In addition, the new routes often result in shorter mileage between end points. For example, the French TGV-SE line reduced the railroad mileage from Paris to Lyons from 318 miles to 264 miles—a 17 percent decrease.¹⁰

Table 1
World Speed Record Data

| Speed (mph) | Date | Country | Equipment |
|-------------|---------|---------|-------------------------|
| 205.6 | 1955 | France | Electric locomotive |
| 236.4 | 2/26/81 | France | TGV Prototype - Turbine |
| 252.9 | 5/1/88 | Germany | ICE (2 Power/3 Coaches) |
| 299.8 | 12/5/89 | France | TGV (2 Power/4 Coaches) |
| 317.3 | 5/9/90 | France | TGV (2 Power/3 Coaches) |
| 317.5 | 5/16/90 | France | TGV (2 Power/3 Coaches) |
| 320.2 | 5/18/90 | France | TGV (2 Power/3 Coaches) |

Sources: "IC-Experimental Smashes the 400 Km/Hr Barrier," *Railway Gazette International* (June 1988), p 335; W.M. deRooy, "TGV-A's Record Breaking 515.3 Km/Hr," *Rail Engineering International*, No. 2 (1990), p 2.

⁸ G. Freeman Allen, "TGV Atlantique—France's Second High Speed Service," *Railway Technology International* (1988).

⁹ T. Rahn and W. Spohrer, p 9.

¹⁰ A. DeTessieres, "An Introduction to the French TGV System," AREA Modern Rail Conference in Vancouver, BC, October 1986 (AREA, 1986), p 390

The route alignments are built, for the most part, with curvature gradual enough to permit top speed operation. The track is specially designed to accommodate the higher speeds, with concrete ties throughout. Even the turnouts are designed for use at much higher speeds than conventional turnouts would permit. Maintenance tolerances are tight and track and roadway inspection is intensive.

High Speed Trains

On the new high speed lines, only the trains specially designed for it are permitted to run. Propulsion is usually straight electric, with current supplied from an overhead system of power lines, or catenary system. The locomotives (referred to as "power cars") are high-horsepower units, and trains are usually run with a power car at each end. The trains are also equipped with high performance braking systems as well as advanced trouble detection and safety systems.

In Japan, the high speed trainsets are powered differently. On the original Tokaido line trains, rather than having power cars at each end, all axles are powered. Newer designs (Series 100) retain a similar format; trains of 16 cars are run with 12 fully powered cars and 4 nonpowered cars.¹¹ Series 300 trains (now being tested) will have 10 powered cars and 6 nonpowered cars.¹²

Compared with conventional equipment, the cars for these new lines weigh less and have lighter axle loads. The trainsets also have a smaller cross-sectional area and advanced aerodynamic shapes to reduce air resistance, which is significant at high speeds. Because the route alignments are built for high speed, the trains have no need for the complex and potentially troublesome tilt-body features. Safe operation around curves at high speeds is enhanced with state-of-the-art suspensions and a lowered center of gravity. (Table 2 shows the center-of-gravity height for selected cars.)

Safety

The safety record of the newest and fastest high speed systems is perhaps unmatched by any other transportation mode, including conventional railroad service. In 1989, after nearly 8 years of service at a maximum speed of 168 mph, the French TGV-SE line celebrated carrying its 100 millionth passenger without any fatalities or injuries.¹³ The only mishap the author is aware of involving the TGV is an incident at the Paris terminal in which, during a switching move, a TGV train (with no passengers aboard) received minor damage to its front end.

The Japanese bullet trains have had an equally enviable safety record. From the beginning of service (in 1964) through 1982, the Tokaido line carried 2 billion passengers without a fatality or injury.¹⁴

¹¹ A. Mochizuki, "A New Series of the Shinkansen EMU Train Made Its Debut," *Japanese Railway Engineering*, No. 94 (June 1985).

¹² "Super Hikari Will Slash Tokyo-Osaka Times," *Railway Gazette International* (January 1990), p 57.

¹³ Scott Sullivan, "The New Supertrains," *Newsweek* (31 July 1989).

¹⁴ Subcommittee of High-Speed Rail Systems of the Committee on Public Transport of the Urban Transportation Division, "High Speed Rail Systems in the United States," *ASCE Journal of Transportation Engineering*, Vol 111, No. 2 (March 1985), p 82

Table 2
Car Center-of-Gravity Data*

| Country | Equipment | Center of Gravity** | Tilt Feature |
|---------|----------------------------|---------------------|--------------|
| Canada | LRC | 51 | No |
| France | TGV-SE | 55 | No |
| Italy | ETR 450 (Pendolino) | 42 | Yes |
| Japan | S-200 (Tohoku/Joetsu) | 45 | No |
| Sweden | X2000 | 49 | Yes |
| USA | Metroliner (Amfleet) | 63 | No |
| USA | Conventional Passenger Car | 84 | No |
| USA | Loaded 100-Ton Hopper | 96 | No |

* Source for data on high speed trains: John A. Bachmann, "HSR Vehicle Performance Characteristics," *ASCE Journal of Transportation Engineering*, Vol 15, No. 1 (January 1989), except for X2000, from ASEA Brown Boveri.

** Measured in inches from top of rail.

and this unblemished record has been maintained since then.¹⁵ Likewise, the newer Sanyo, Tohoku, and Joetsu lines have operated without fatality or injury.

Two other operations at the low end of the high speed category are also without fatality or injury: one in Canada and the other in England.¹⁶ Both employ diesel-electric power for propulsion. The Canadian trains (LRC) have operated since 1975 at a maximum speed of 120 mph and the English trains (HST) since 1976 at a maximum speed of 125 mph.¹⁷

The safety records of these systems have clearly proven the ability of trains to operate safely in the high speed range.

¹⁵ L.D. Shen and A. Farooqi, "Florida High-Speed Rail: An Ambitious Plan for the Future," *ITE Journal* (Institute of Transportation Engineers [ITE], September 1989), p 12

¹⁶ L.D. Shen and A. Farooqi, p 12.

¹⁷ Eric H. Sjöqvist, pp 61, 63

3 HIGH SPEED FREIGHT TRANSPORT

The use of railroad transport for mobilization implies the need to haul freight. In fact, a series of transportation system capability studies performed by the Military Traffic Management Command (MTMC) to assess mobilization capabilities at various military installations indicates that both Army and commercial railroads would be needed for transporting the heaviest equipment, particularly tracked vehicles such as the M1 tank.

From the previous chapter, which summarizes existing high speed railroad systems, it is apparent that today's high speed operations are intended for carrying passengers, with perhaps some provision for the transport of small packages and express. (Two mail trains currently run on the TGV-SE line.) The current exclusion of heavy freight from high speed transport is not only based on economics, but also on the technological obstacles to handling heavy freight at speeds over 100 mph.

The requirements for safely carrying passengers on high speed trains with high rates of acceleration present engineers with challenges that approach the physical limitations of conventional railroad transport. These technological challenges are even greater for carrying heavy freight at high speed.

This chapter discusses how the requirements for carrying passengers and freight differ, and the technological challenges that confront engineers in the design, operation, and maintenance of high speed freight railroads.

A Difference in Weight

A comparison between a French TGV-SE train and a hypothetical tank mobilization movement can illustrate the great differences in weights between passenger and heavy freight operations. This information is summarized in Table 3.

According to MTMC information, one flatcar designed for carrying the M1 tank weighs 47.5 tons. Adding to that its load of two M1 tanks (at 62.9 tons each) gives a total car weight of 173.3 tons. Thus, it takes about 2-1/2 loaded flatcars to equal the weight of one fully loaded TGV trainset. To make a similar comparison based on Table 3, the M1 freight weighs about the same as 20 fully loaded TGV trains.

One alternative to reduce total train weight would be to run many short trains rather than a few longer ones. This has both economic and practical limitations because each train requires an engine and operating crew, and the dramatic increase in number of trains could create traffic flow problems.

It is unlikely that new designs for high speed freight cars could result in any significant weight reductions either. Whereas the load of passengers plus baggage adds only about 10 percent to the weight of an empty lightweight passenger car, the bulk of a freight train's weight is in the load itself; the load capacity of a freight car is commonly about 3 times the car's empty weight. In addition, the strength to carry this level of loading, along with the requirements to withstand dynamic forces at higher speeds over many years' service would tend to offset any reduction in freight car weight through improved design and the use of lighter weight materials.

Table 3

Weights of TGV Equipment and a Mobilization Train of M1 Tanks

TGV-SE

| | |
|--------------------------------|----------------|
| Empty Weight: in working order | 423 tons |
| Load: 386 passengers + baggage | 39 |
| TOTAL | <hr/> 462 tons |

M1 Freight

| | |
|-----------------------------|-----------------|
| Engines: three 6-axle units | 540 tons |
| Cars: 50 flats (140-ton) | 2375 |
| Load: 100 M1 tanks | 6290 |
| TOTAL | <hr/> 9205 tons |

Sources: Eric H. Sjokvist, p 72; G. Freeman Allen, p 74.

Clearly, freight operations result in train weights many times those typical of passenger operations. The significance of these differences in total train weight will become more apparent in following sections, especially those that address propulsion and braking requirements.

Power Requirements

Power requirements are dictated primarily by four factors:

1. Train resistance
2. Maximum speed
3. Gradient and alignment of the track
4. Acceleration requirements.

The amount of power needed for a train begins with the requirement to get the train moving and keep it moving. A relatively small amount of power is needed to move a train on level tangent track at low speed. In this case, power is primarily used in overcoming the frictional resistance of wheel bearings and the rolling resistance of the wheels on the track. This portion of train resistance has components that are relatively constant and ones which vary directly with the speed of the train.

An additional component of basic train resistance is air resistance, which varies directly with the square of train speed. It relates to the resistance encountered by the train moving at speed in still air (no wind).

These resistance factors lead to the basic expression for train resistance, often referred to as the Davis equation. Although modified over the years, it is still a standard in the railroad industry.¹⁸ In general form it can be expressed as:

$$R = A + Bv + Cv^2 \quad [\text{Eq 1}]$$

where R = resistance for a single car or engine (or train),

A , B , and C = coefficients that depend on type of equipment and operating conditions, and

v = speed of train.

Coefficients for some of the world's high speed and conventional trains are listed in Table 4.

Ascending grades add a resistance of 20 lb per ton of train weight for each percentage of incline. Curves also add resistance, commonly taken as 0.8 lb per ton of train weight for each degree of curvature.¹⁹

Additional power is required to accelerate a train. For each ton of train weight, about 100 pounds of force is needed for each mile per hour/second of acceleration.²⁰ Power must also be supplied for operating engine auxiliary equipment and, on passenger trains, for lights, air handling systems, etc. Power is used in rotating all wheels, and a small percentage of total power is lost due to inefficiencies inherent in the engine.

Currently, all systems that provide service above the minimum level to qualify as high speed have straight electric propulsion supplied through a catenary system. Straight electric propulsion is, in fact, a requirement for practical operation of a high speed system.²¹ This practical requirement is based on the amount of power needed to operate at high speed. Electric locomotives produce more power per ton of locomotive weight than do diesel or gas turbine locomotives; stated simply, electric locomotives provide more power in about the same size package. A comparison might be made between the British diesel HST and Amtrak's electric Metroliner service. Both are intended for a top speed of 125 mph and were designed within 2 or 3 years of each other. One HST power car is 57.7 feet long, weighs 72 tons, and can produce about 1950 continuous-traction horsepower.²² An Amtrak AEM-7 locomotive is 51.1 feet long, weighs 100.1 tons, and can produce about 5500 continuous-traction horsepower. At 55 hp per ton of weight, the AEM-7 doubles the HST's output of 27 hp per ton.²³

¹⁸ *Manual for Railway Engineering*, Chapter 16 (AREA, 1989-90), p 16-2-2.

¹⁹ *Manual for Railway Engineering*, p 16-2-3.

²⁰ *Application of Diesel-Electric Locomotives* (General Electric, Transportation Systems Division), p 9; *Manual for Railway Engineering*, p 16-2-4.

²¹ Shinya Kikuchi, *High Speed Passenger Rail System: Concept, Components, and Planning* (ITE, 1984), p 3-1; Subcommittee of High-Speed Rail Systems, p 81; Eric H. Sjøkvost, p 79.

²² Eric H. Sjøkvost, p 62.

²³ ASEA Traction ABB, manufacturer's literature (1986).

Table 4
Train Resistance Coefficients

| Country: Train | Total Train Weight (Tons) | Equation Coefficients | | |
|--|------------------------------|-----------------------|----------|----------|
| | | <u>A</u> | <u>B</u> | <u>C</u> |
| France: TGV-SE | 462 | 0.86 | 0.014 | 0.000367 |
| Great Britain: 20-Car Freight | 2,000* | 3.5 | 0.055 | 0.00151 |
| Great Britain: HST | 409 | 0.64 | 0.0065 | 0.000450 |
| Japan: 8-Car Tokaido | 560* | 1.23 | 0.025 | 0.000388 |
| Japan: 12-Car Tokaido | 840* | 1.73 | 0.051 | 0.000573 |
| USA: 100-Car Unit Train (100-Ton Hoppers) | 14,000 | 17 | 0.14 | 0.008 |
| Idealized TGV-Style 7-Car Freight * | 1,570 | 2.0 | 0.021 | 0.000477 |

*Estimated figures

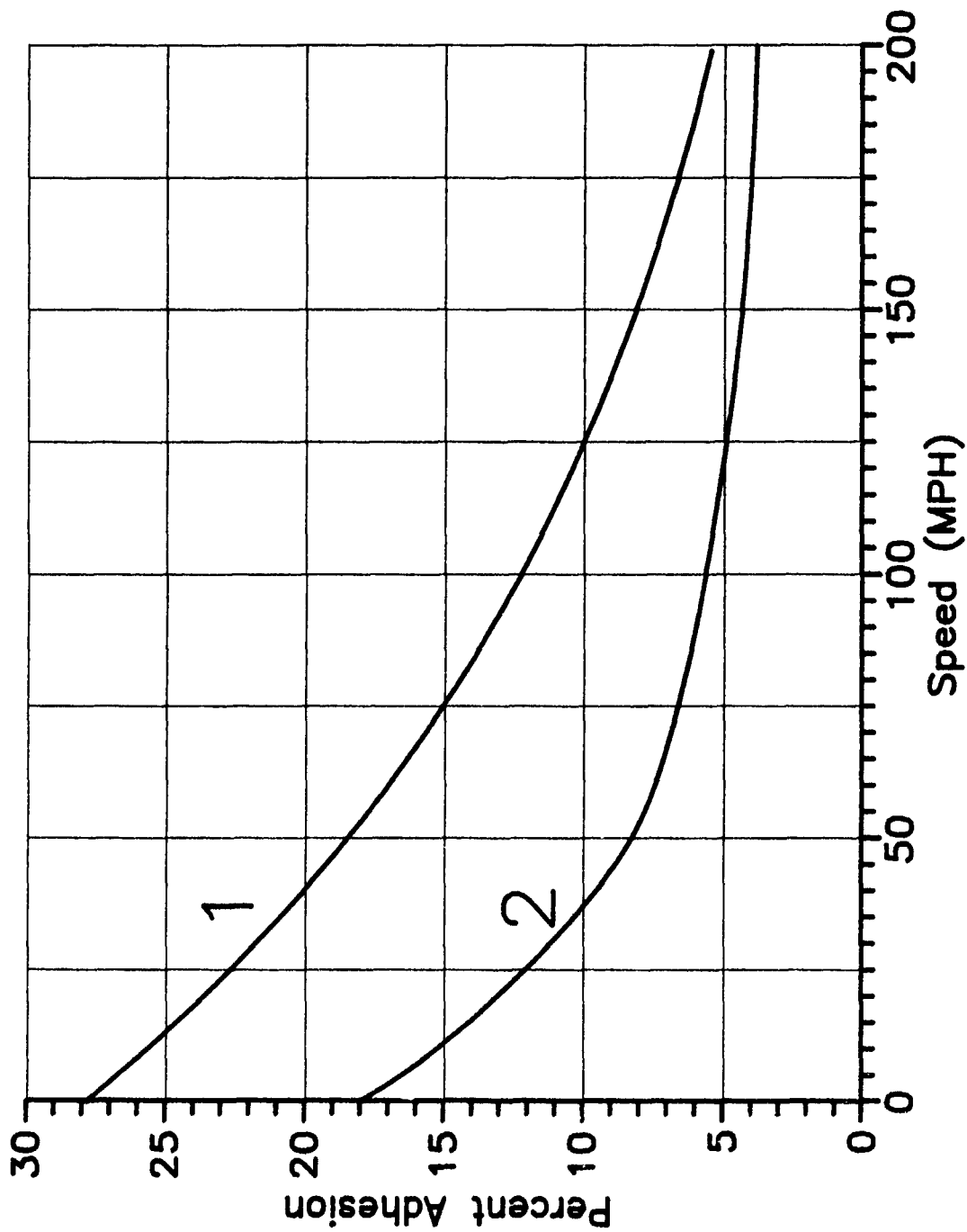
Sources: *Manual for Railway Engineering*, p 16-2-2; and Eric H. Sjökvist, p 58.

It should be clear that as train speeds and acceleration demands increase, so does the power requirement. As illustrated later in Chapter 5, supplying sufficient power—especially for high speed freight service—presents a considerable technological challenge.

Adhesion and Tractive Effort

The force supplied by an engine to pull a train is usable only up to the limits of wheel-to-rail adhesion. Force applied beyond this limit simply causes the powered wheels to spin. The amount of adhesion depends on wheel tread, rail surface condition, and train speed.

Adhesion is simply the coefficient of friction between the wheel tread and the rail surface, usually expressed as a percentage. The highest adhesion is available at starting or low speeds on clean, dry rail. In such cases, adhesion may be as high as 30 percent. This means that propulsive force may be applied to the rail up to an amount equaling 30 percent of the weight resting on the powered wheels. Adhesion decreases if the wheel tread and rail are wet or covered with grease or oil. In this case, starting or low



1: Favorable Rail Condition 2: Unfavorable Rail Condition

Figure 2. Available adhesion as a function of train speed.

speed adhesion may be only 15 percent.²⁴ Adhesion also decreases with increasing speed, as illustrated in Figure 2, which shows the relationship between adhesion and speed for both favorable and unfavorable rail surface condition.

The available propulsive force (tractive effort) depends on the power available from the engine, the amount of weight resting on the powered wheels, speed, and the coefficient of friction (adhesion) between the powered wheels and the rail. Below the maximum rated value for a locomotive, tractive effort can be approximated by the following formula:

$$TE = 375 \times hp / v \quad [Eq\ 2]$$

where TE = tractive effort (pounds)

hp = locomotive horsepower available for traction

v = speed (mph).

As previously noted, power demands increase with acceleration, speed, and grade. However, as speed increases, it is clear that available propulsive force decreases due to decreasing tractive effort, increasing train resistance, and decreasing adhesion. Where tractive effort capability is beyond the limits of adhesion, an increase in usable tractive effort may be obtained by adding weight to the engine (over the powered wheels), but this extra weight also requires additional power to move and soon reaches practical axle load limits.

Braking and Stopping Distance

The ability to stop a train depends on its weight, speed, and available braking force. As with propulsive force, for conventional braking systems, braking force is limited by wheel-to-rail adhesion. Any force applied to a wheel beyond this limit will cause the wheel to lock and slide along the rail.

The latest development in braking for high speed trains is the eddy current brake, which is used to supplement conventional brakes. The system consists of a series of electromagnets which, when lowered near the top rail surface, produce a current in the rail (an eddy current) that creates an opposing magnetic field. This produces a magnetic drag that helps stop the train. The addition of eddy current brakes to a train adds expense in equipment and control systems, and also adds extra weight.

The German ICE trains are equipped with eddy current brakes. They are effective above 25 mph and are said to increase braking rate (deceleration) by about 40 percent, from a maximum of 1.6 mph/sec (without the eddy current brake) to 2.2 mph/sec (with the eddy current brake in use).²⁵ In operation, these brakes are held about 1/4 in. above the rail surface.

The control of brakes in freight service presents a problem not typically found in passenger service. As noted above, when an empty passenger car becomes completely filled with passengers, its weight increases by about 10 percent. When an empty freight car is fully loaded, its weight commonly increases

²⁴ William W. Hay, *Railroad Engineering* (John Wiley & Sons, 1982), p 103

²⁵ Klaus Becker-Lindhorst, "German ICE Braking," *Railway Technology International* (1988)

by about 300 percent. Since required braking forces (to stop within a given distance) vary with a car's weight and are limited by adhesion, effective and even braking depend on having a brake system that can sense, and adjust to, the weight of each car. This requirement complicates brake system design.

Stopping distance is proportional to the square of the speed.²⁶ Using a constant retarding force, for example, a speed increase from 60 to 85 mph would result in doubling the stopping distance. Stopping distance is also proportional to the brake retarding force, which depends on the coefficient of friction between the brake shoe and wheel (for standard or disc brakes) and is limited by wheel-to-rail adhesion. Both wheel-to-shoe friction and wheel-to-rail adhesion decrease with increasing speed. Retarding force is also limited by the heat buildup due to friction in the wheel and brake shoe.

Actual stopping distance for a train must be determined by test, as braking forces vary with speed. However, when the average braking (deceleration) rate is known, approximate stopping distance can be estimated from the following formula:

$$SD = v^2 / (7200 \times BR) \quad [Eq\ 3]$$

where SD = stopping distance in miles

v = speed in mph

BR = average braking (deceleration) rate
in mph/sec.²⁷

Using this formula, Figure 3 shows stopping distances for various average braking rates from 0.7 to 2.2 mph/sec. As a reference, an average braking rate of 1.3 mph/sec is considered good braking performance for conventional railroad operations.

To summarize, stopping distances for high speed operation increase dramatically due to the lowered wheel-to-rail adhesion and a smaller brake shoe-wheel friction coefficient.

Grade Crossings

In his article on "High-Speed Rail Track Design," Jan H. Zicha states that "Necessary improvements include the removal of at-grade crossings..."²⁸ The incompatibility of grade crossings on high speed lines has been well recognized. When maximum speed was raised from 100 to 130 mph in the Northeast Corridor in 1969, difficulties with grade crossings were soon apparent, and within the next several years all of these crossings were eliminated.

New high speed lines, such as used by the Shinkansen in Japan and the TGV in France, have been built without any grade crossings. Unlike at slower speeds, hitting a vehicle at high speed would involve

²⁶ William W. Hay, p 167.

²⁷ *Management of Train Operation and Train Handling* (Air Brake Association [ABA], 1977), p 198.

²⁸ Jan H. Zicha, "High-Speed Rail Track Design," *ASCE Journal of Transportation Engineering*, Vol 115, No. 1 (January 1989), p 80.

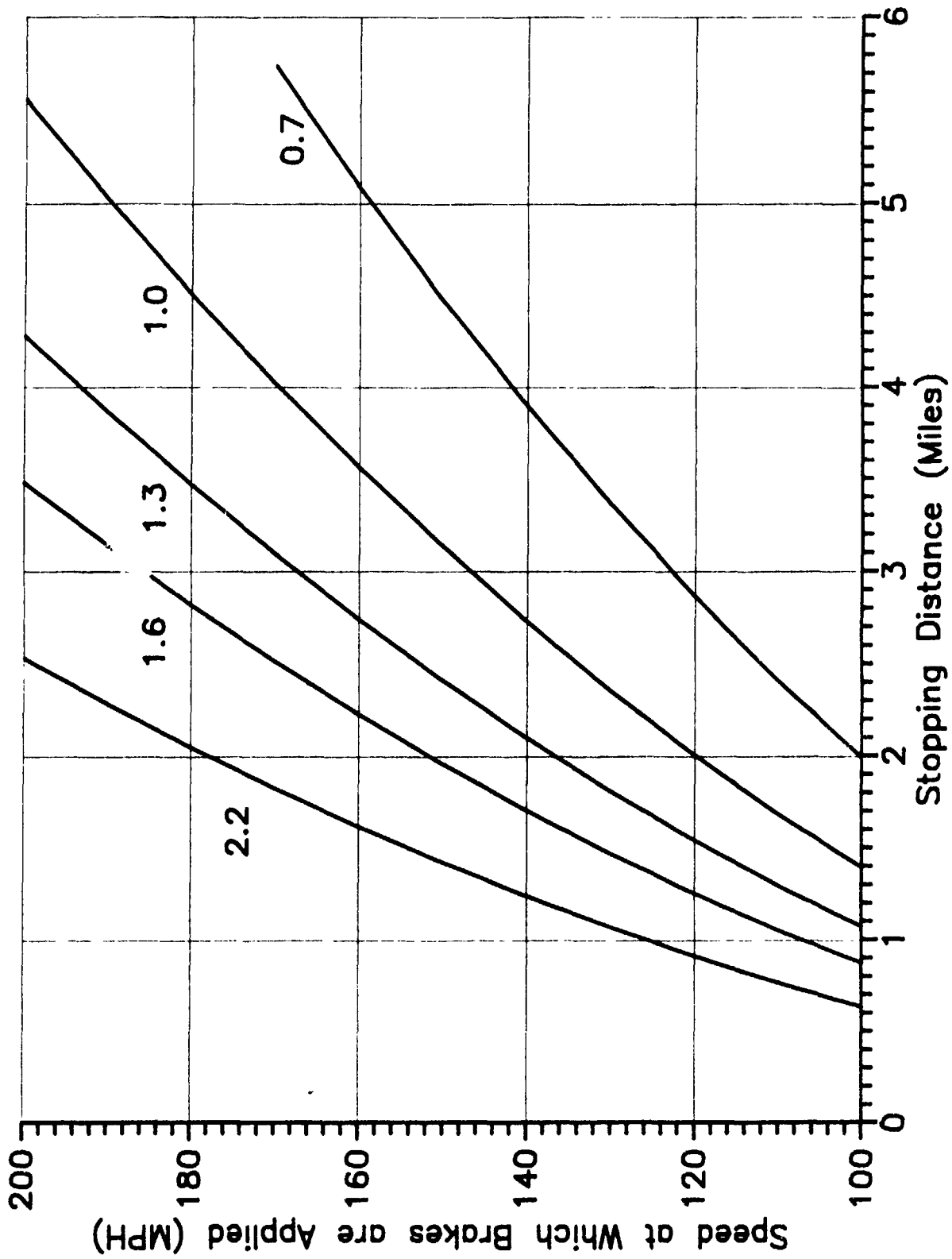


Figure 3. Approximate stopping distance on level track for varying braking rates.

such a high-energy impact (proportional to the square of the speed) that the likelihood of derailment and serious damage to a train is great. Even if no passengers were involved (e.g., a freight train or empty passenger train) such a collision would mean almost certain serious injury or death for the train crew. Thus, as Zicha states, it is a given that high speed operation excludes grade crossings.

Dynamic Loads and Wheel/Rail Impacts

In addition to the weight of an engine or car on its wheels, there are other forces that develop as a result of motion and speed. These forces act in combination with imperfections in track geometry and wheel and rail surfaces, often taking the form of vertical impacts of the wheel on the rail. The term "dynamic load" commonly refers to the sum of these forces.

Wheel and rail surface imperfections and worn areas are a significant source of dynamic impact.

A 1/4-in. flat spot, which is considered quite small on a 40-in. diameter wheel (a common size for locomotives in the U.S.), has been found to create a total dynamic loading factor as high as 3.0 at 125 mph, and up to about 5.0 at 155 mph.²⁹

Increased wheel loads also cause increased dynamic loading. In France, it has been observed that a 22-ton axle load at 60 mph can create the same level of dynamic loading as a 19-ton axle load moving at 170 mph.³⁰ Thus, to keep track maintenance costs down, axle loads on TGV lines have been limited to 18.7 tons.

Plans for the French and German railroads call for certain freight operations to begin operation at 100 mph. These trains would haul specially designed, fully enclosed container cars with axle loads up to about 19.8 tons.³¹ (The common axle load limit in the United States is 33 tons).

High dynamic loading and its damaging effect on track have most often been associated with a combination of heavy weight and high speed. However, recent research shows that certain higher vibrational frequencies generated at high speed may be of concern, even with lighter cars.³² These higher frequencies are said to increase ballast deterioration and subgrade settling.³³

Suspension Systems

The term "suspension" refers to the "resilient system through which a car body is supported on its wheels."³⁴ Without a well designed and well tuned suspension system, train operation at high speed is not practical. As noted in the previous section, even small wheel and track irregularities can induce large dynamic forces at high speed. These forces must be sufficiently damped to minimize wear and tear on track and trains, and to provide an acceptably smooth ride for passengers or freight.

²⁹ Jan H. Zicha, 1989, p 70.

³⁰ Jean-Pierre Pronost, "Track and Structure Maintenance for 170 M.P.H. on the New Paris-Lyon TGV Line," AREA Modern Rail Conference, Vancouver, BC, October 1986 (AREA, 1986), p 391.

³¹ "Freight speed rises to 160 km/hr," *Railway Gazette International* (June 1990), p 455.

³² B. Rajaram, "A New Theory of Rail-Wheel Interaction," *Rail International*, Vol 15, No. 4 (April 1984).

³³ Jan H. Zicha, 1989, pp 72, 79.

³⁴ *Comprehensive Railroad Dictionary* (Simmons-Boardman Books, Inc., 1984), p 142.

To function effectively, suspension designs must be matched to the weight of the vehicle. As with braking systems, suspension designs for freight cars capable of carrying heavy freight at high speed present a considerable challenge to engineers. For light passenger equipment (TGV-A) the gross weight of a car may increase from 33 tons to 38 tons with the addition of passengers and luggage, or about 15 percent. For freight equipment, the weight change from empty to fully loaded may be from 33 tons to 133 tons—a 300 percent increase. Thus, the suspension system of a high speed freight train will have to be effective over an extremely wide range of weights.

Derailment Consequences

When a train derails, the track, roadbed, and nearby structures become, in effect, part (or all) of the train's brake system; they end up absorbing the kinetic energy of the train's motion. This energy is proportional to the weight of the train and the square of its speed, and is primarily responsible for the destruction which occurs during a derailment.

The significance of this for high speed freight operation can be seen in a comparison between a French TGV-SE train and a 50-car train carrying M1 tanks. If both are traveling at 60 mph, the freight train has about 20 times the kinetic energy of the TGV. If the freight increases speed to 85 mph its kinetic energy doubles to 40 times the energy of the TGV traveling at 60 mph.

The energy of a heavy high speed train creates a potential for tremendous destruction resulting from a derailment, and offers considerable challenge to designers in creating engines and cars with sufficient strength to withstand derailment impacts and forces. Increased strength typically implies increased weight, but, at high speeds, extra weight can significantly reduce train performance or increase power and brake requirements. And when propelled at high speed, any increased weight adds to the potential destructive energy available.

4 ROUTE ALIGNMENT AND TRACK REQUIREMENTS

In a paper entitled "High-Speed Rail Systems in the United States" prepared by the American Society of Civil Engineers (ASCE), track requirements for the operation of high speed trains are summarized with the statement that the track must be "built and maintained to much more demanding specifications and closer tolerances than conventional, lower-speed tracks."³⁵ To illustrate how demanding these requirements are, the paper notes that track on the French TGV-SE line is maintained to vertical and horizontal tolerances four times stricter than allowed for Federal Railroad Administration (FRA) Class 6 track, which permits a top speed of 110 mph and is the highest speed FRA track class.

Generally, operation above 125 mph requires major changes in route alignment, track construction, and track maintenance.³⁶ This chapter will address these requirements in more detail. The significance of some of these requirements for high speed operation will be quantified with examples in Chapter 5.

Curves and Superelevation

One of the first considerations in operating over a route at high speed is the ability to safely and comfortably negotiate curves. To permit satisfactory curve operation at even moderate speeds, superelevation is required: the outside rail of the curve must be raised above the elevation of the inside rail. When in perfect balance, the speed of the train and the amount of superelevation match so forces directed toward the outside of the curve (caused by the train's speed) equal the forces directed toward the inside of the curve (caused by gravity and superelevation). In practice, a certain amount of unbalance is allowed.

The amount of allowable unbalance depends first upon safety. At the extreme, the unbalance must be limited so the centrifugal forces pulling the train toward the outside of the curve, in combination with a strong wind, will not: (1) turn the train over or (2) cause a derailment by forcing the wheel flanges up over the outside rail.

In practice, superelevation limits are set by passenger comfort and maintenance considerations. By safety criteria alone, superelevation unbalance might allow a train to safely negotiate a curve but still create centrifugal forces that knock people down in an aisle or cause coffee cups to fly across the car. And, especially with freight traffic, the high end "just safe" degree of unbalance would probably cause rapid wheel and rail wear, because wheel flanges would be pushed hard against the side of the outside rail.

High amounts of superelevation, however, can result in wheel and rail wear on the *inside* of a curve. This is especially true when a train operates around a curve at speeds much slower than the balancing speed. In this case, the train "falls into the curve" so gravity pulls the wheel flanges hard against the inside rail. Thus on curves with superelevation, too little speed can be as undesirable as too much.

Many studies have been conducted to determine acceptable superelevation unbalance, especially in recent years with the emergence of high speed passenger operations. Since 1914, the standard allowable

³⁵ Subcommittee of High-Speed Rail Systems, p 81.

³⁶ Shinya Kikuchi, p 3.1.

unbalance in curves in the United States has been 3 in.³⁷ This rule means that a train might, for example, operate on a curve with 2 in. of superelevation at a speed that would require 5 in. of superelevation for perfect balance.

Table 5 shows the maximum curvature around which trains can comfortably operate at the listed speeds and superelevations. The table entries were determined by using the standard expression:

$$E = 0.0007 \times D \times v^2 \quad [\text{Eq 4}]$$

where E = total (balanced + unbalanced) superelevation (in.)
 D = degree of curve (the radius of a 1-degree curve is 5730 feet)
 v = speed (mph).³⁸

In keeping with the higher unbalance sometimes allowed for the lower center-of-gravity high speed trains,³⁹ an unbalance of 4 in. is used as the basis for Table 5. The maximum allowable curvature is determined as follows:

$$D = (E + 4)/(0.0007 \times v^2) \quad [\text{Eq 5}]$$

where D = curvature (degrees)
 E = superelevation (in.)
 v = speed (mph).

As the laws of physics dictate the requirements for operation around curves, the allowable curvature is inversely proportional to the square of the speed. This general rule can be seen in Table 5; the allowable curvature for operating at 120 mph, for example, is four times less than that allowed at 60 mph. The maximum curvature using standard AREA practice is shown in the column labeled 5 in. Table 6 shows the maximum degree of curvature and superelevation allowances for several high speed lines.

Referring to the columns in Table 5 for 4 in. and 7 in., and for speeds between 100 and 140 mph, it can be seen that an increase in speed of just 20 mph around a given curve would require an extra 3 in. of superelevation. For example, at 100 mph and with 4 in. superelevation, a train can operate around a 1.1 degree curve. At 120 mph, operation around the same curve would require 7 in. of superelevation. From Table 5 it is also clear that operation at the low end of the high speed range permits a maximum curvature of about 1 degree. Therefore, if high speed freight trains are to support a mobilization effort they must use routes mostly limited to curvature in this range. The implications of this limitation for high speed service on existing track are covered in Chapter 6.

Grades

The amount of force required to lift a train up a grade is proportional to the steepness of a grade. Thus it takes 3 times the force to pull a train up a 3 percent grade as it does a 1 percent grade.

³⁷ F.E. Dean and D. Ahlbeck, "Criteria for High-Speed Curving of Rail Vehicles," presented to ASME Winter Annual Meeting, December 1972 (ASME, 1979), p 2

³⁸ William W. Hay, p 602.

³⁹ F.E. Dean and D. Ahlbeck, p 3

Table 5**Maximum Allowable Curvature for Different
Speeds and Superelevations (at 4 in. Unbalance)**

| Speed (mph) | Actual Superelevation | | | |
|------------------------|----------------------------------|--------------|--------------|--------------|
| | 7 in. | 6 in. | 5 in. | 4 in. |
| 60 | 4.4* | 4.0 | 3.6 | 3.2 |
| 80 | 2.5 | 2.2 | 2.0 | 1.8 |
| 100 | 1.6 | 1.4 | 1.3 | 1.1 |
| 120 | 1.1 | 1.0 | 0.9 | 0.8 |
| 140 | 0.8 | 0.7 | 0.65 | 0.6 |
| 150 | 0.7 | 0.65 | 0.55 | 0.5 |
| 160 | 0.6 | 0.55 | 0.5 | 0.45 |
| 180 | 0.5 | 0.45 | 0.4 | 0.35 |
| 200 | 0.4 | 0.35 | 0.3 | 0.3 |

*Data are expressed in degrees of curvature.

On western U.S. railroads, the ruling grades (the steepest grades of significant length) are typically limited to 2.2 percent. For operation in the United States, 3 percent is a common upper limit for freight trains. The power requirements for steeper grades are considered too large for practical operation.

The TGV-SE line in France was built with grades as steep as 3.5 percent. These steep grades were accepted as a reasonable tradeoff for the costs saved through a reduction in number and length of bridges, a 17 percent reduction in route mileage, and the avoidance of tunnels.⁴⁰ The steep grades are made operationally possible by taking advantage of the momentum of high speed in combination with the aerodynamic advantages of the train's reduced cross-sectional area.

⁴⁰A. DeTessieres.

Table 6 shows the maximum grades for several high speed lines.

Turnouts

As the general literature points out, faster speeds are only useful when they result in a significant reduction in trip time. This requires that high speed be maintained for as long a period as possible, with a minimum number of stops and speed reductions. To minimize speed reductions, it is stated that, "The latest design of high-speed crossovers and turnouts is critical for maintaining high-speed travel time."⁴¹

In conventional operations, turnouts permitting the highest speeds have typically been Number 20s in an equilateral configuration. These may allow speeds up to 70 mph—well below even the low end of high speed (125 mph).

Turnouts designed for the new high speed routes are exemplified by those on the French TGV-SE line. Of 135 total turnouts, 87 are the new high speed type. These incorporate very low frog angles and movable point frogs. There are 60 Number 46s, which allow 100 mph operation, and 27 Number 65s, which permit 140 mph.⁴²

Track Geometry Tolerances

Track geometry refers to the relative position of the rails: vertically, horizontally, and of one rail with respect to the other. Especially for high speed operation, track geometry deviations must be kept small due to safety, track and equipment maintenance, and ride quality considerations.

As noted at the beginning of this chapter, the track geometry tolerances on the French TGV-SE line are four times stricter than those for the highest FRA track class. On Japan's Tokaido line, where the maximum speed is 137 mph, remedial action is required when track gage becomes 1/4 in. wide and when crosslevel deviates by 3/16 in. from design value.⁴³ In Great Britain, the respective values for 125 mph operation are 1/4 in. for gage, 3/16 in. for crosslevel on curves, and 1/8 in. for crosslevel on tangent track.⁴⁴ Depending on the frequency generated, a defect (or defect combination) on the Tokaido line that produces a lateral acceleration of 0.2g calls for maintenance.⁴⁵

It is clear from the literature on high speed track that such tight tolerances are necessary and have been successfully maintained during the operation of these lines, but at no small effort.

Maintenance

The largest maintenance activities on high speed lines include inspection for, and correction of, track geometry and turnout defects.⁴⁶ Cars that measure track geometry defects and excess accelerations (ride

⁴¹ Jan H. Zicha, 1989, p 81.

⁴² Jean-Pierre Pronost, p 392

⁴³ Jan H. Zicha, 1989, p 77

⁴⁴ Jan H. Zicha, 1989, p 78

⁴⁵ S. Takahara and Y. Sato, p 3

⁴⁶ Jean Pierre Pronost, p 393

Table 6
Route and Speed Data for Several High Speed Lines

Maximum^a

| Country | Operation | Allowable Speed (mph) | Grade (Percent) | Curvature (Degrees) | Superelevation Actual/Unbalance (Inches) |
|------------|------------------------------|-----------------------------|--------------------|------------------------|--|
| France | TGV - SE | 168 | 3.5 | 0.44 | 7.1 / 3.5 |
| | TGV - A | 187 | 1.5 ^b | 0.44 ^c | 7.1 / 5.1 ^d |
| Germany | ICE ^e | 155 | 1.25 | 0.25 ^f | 6.0 / 2.8 |
| G. Britain | HST | 125 | 2.7 | 2.2 | 5.9 / 4.3 |
| Italy | Rome-Florence (Pendolino) | 125 | 0.85 | 0.6 | 6.3 / 5.1 ^g |
| Japan | Tokaido | 137 | 2.0 | 0.7 | 7.1 / 1.2 |
| | Sanyo | 143 | 1.5 | 0.44 ^h | 6.1 / 1.0 |
| | Tohoku | 150 | 1.5 | 0.44 | 6.1 / 0.6 |
| | Joetsu | 170 | 1.5 | 0.44 | 6.1 / 1.0 |
| Spain | ⁱ | 155 | 1.25 | 0.55 | 4.7j / 4.5 |

Notes

^a - Maximum speeds are not necessarily operated on the maximum grades and curves.

^b - With a few exceptions at 2.5 percent.

^c - Only two curves on the line are this sharp.

^d - 5.1 in. on the sharpest curves, otherwise 3.9 in.

^e - Service scheduled to begin during 1991; data are for newly constructed lines only.

^f - With a few exceptions at 0.34 degrees.

^g - Trains have tilt-body feature.

^h - With a few exceptions at 0.5 degrees.

ⁱ - Service planned to begin in 1992, with TGV-type trains running between Madrid and Seville.

^j - Calculated value.

Sources: Subcommittee of High-Speed Rail Systems; Jan H. Zicha, *Maglev Systems—Advantages, Risks, and Uncertainties* (DeLeuw, Cather, and Co., Washington, DC, 1985); *Railway Gazette International* (February 1988 and February 1990); *Japanese Railway Engineering* (December 1985 and September 1986).

quality) are run over Japan's Tokaido line every 10 days⁴⁷ and on the French TGV-SE line every week.⁴⁸ On U.S. heavy traffic freight lines, where wheel loads are about 70 percent higher than those on the TGV and Tokaido lines, track geometry cars are commonly run about every 2 to 3 months. Out-of-face (large scale) track surfacing is carried out every 2 years on the TGV-SE line,⁴⁹ while every 3 years is common on U.S. heavy traffic freight lines.

The costs related to maintenance on high speed lines are discussed in Chapter 6.

⁴⁷ S. Takahara and Y. Sato, p. 6

⁴⁸ Jean-Pierre Pronost

⁴⁹ Jean-Pierre Pronost, p. 396

5 THEORETICAL TRAIN PERFORMANCE COMPARISONS

In this chapter, some of the concepts presented in Chapters 3 and 4 will be illustrated with several hypothetical but realistic examples. In these examples the performances of two trainsets will be compared. One trainset is a standard TGV-SE train, as operated in France since 1981. The other (M1 Freight) is an idealized high speed freight with the general configuration of a TGV train. This M1 freight train consists of seven fully enclosed, streamlined 140-ton flatcars carrying M1 tanks, plus a power car (engine) at each end. Each power car is a hypothetical six-axle version of Amtrak's four-axle AEM-7 locomotive. (The AEM-7 is an electric locomotive of Swedish design. It is used to haul trains in the Northeast Corridor and is currently among the best performing locomotives in the world).

As the TGV train is among the most advanced (or "ideal") passenger trains in the world, the M1 freight train in these examples is intended to represent an advanced design with ideal performance characteristics. Currently, the author knows of no design concept for such a train.

An occasional comparison to current U.S. passenger and freight operations is made to supplement the examples.

Trainset Performance Data

With a few exceptions, the performance data for the TGV-SE trainset are as given in the reference material. The data for the idealized seven-car M1 freight are based on a combination of existing equipment, with some additional design and performance improvement assumed.⁵⁰

The freight trainset was pictured to have the same aerodynamic shape as a TGV-SE, but with a 30 percent larger cross-sectional area to accommodate the flatcars and M1 tanks. Power car characteristics are based on an "improved" six-axle AEM-7. The cars are assumed to be like the current 140-ton series, but with high speed trucks, brakes, and suspension, and a lightweight streamlined shell that just clears the loaded tanks and covers the area beneath the car floor. This train would be the same length as the TGV train and would carry 14 M1 tanks. On the outside, it would look like a taller and wider TGV with no windows in the cars.

In developing the train resistance equation for the idealized freight, coefficients "A" and "B" were determined by extrapolating the Schmidt and Tuthill data⁵¹ from a 18.7-ton axle load up to a 30-ton axle load. The percentage of change in the coefficients from 18.7 to 30 tons was then figured and the results from the two data sets were averaged. This average percentage of change was then applied to the train resistance equation used for the TGV-SE.⁵² The ratio of cross-sectional areas between the idealized freight and the TGV-SE was used to determine coefficient "C."⁵³

The tractive effort curves are based on the standard formula for tractive effort (see **Adhesion and Tractive Effort** in Chapter 3), up to an estimated maximum output. The "short time" ratings are estimates

⁵⁰ Technical Manual (TM) 55-2220-058-14, *Transport of Cargo on the Railway Flat Car* (HQDA, January 1984), pp 2-1, 2-2, 4-1.

⁵¹ William W. Hay, p 74.

⁵² Eric H. Sjöqvist, p 58.

⁵³ Eric H. Sjöqvist, p 56.

of 1-hour ratings for the propulsion equipment, which is an industry standard; they indicate the performance that can be obtained for up to one continuous hour without overheating the traction motors and other electrical propulsion equipment.

Basic data for the two example trains are listed in Table 7. Figures 4 through 8 show the resistance curves, and continuous and short time tractive effort are shown in Figure 9.

Examples

The first two examples address the performance requirements and capabilities of the TGV-SE and idealized M1 freight at 125 mph. A summary of the results is shown in Table 8. From this table, it is clear that both trains can easily run at 125 mph on level track. With favorable (dry) rail conditions, only the TGV-SE can climb a 1.5 percent grade at this speed; the M1 freight would have to reduce speed to 110 mph to make this grade. With unfavorable rail conditions the TGV-SE could not maintain 125 mph on the 1.5 percent grade either. Under these conditions, the idealized M1 freight could either maintain 125 mph on (at most) a 0.76 percent grade, or climb the 1.5 percent grade at about 60 mph.

Even with favorable rail conditions, the TGV-SE cannot accelerate at 0.3 mph/sec from 125 mph on the 1.5 percent grade, and the idealized M1 freight falls far short of this capability.

The last example addresses the TGV-SE's performance at its top service speed of 168 mph. From Figure 9, line 2 (short time), tractive effort at 168 mph is about 23,000 lb. Checking adhesion under favorable rail conditions (Figure 2, line 1), the maximum available traction could be about 6.7 percent of the train's total traction weight of 214 tons (Table 7), or $0.67 \times 428,000$ lb, which equals 28,676 lb. The smaller quantity—tractive effort, in this example—governs the situation, so the train's 23,000 lb is available. From Figure 4, line 1, the train resistance at 168 mph is about 13,500 lb. Thus, the available grade-climbing force is 9500 lb (23,000 lb - 13,500 lb). From Figure 5, reading across from 9.5 to line 1, the maximum grade the TGV-SE can climb at 168 mph is about 1.0 percent.

Summary of Examples

Especially for the idealized seven-car M1 freight, the examples show that at the lower limit of high speed, grade-climbing and acceleration performance are modest at best, even with no allowance for side or head wind. At 125 mph the M1 freight, with some allowance for wind and imperfect rail conditions, could probably not handle more than about a 0.8 percent grade. This might suggest that the trains are insufficiently powered, so a relative comparison is useful.

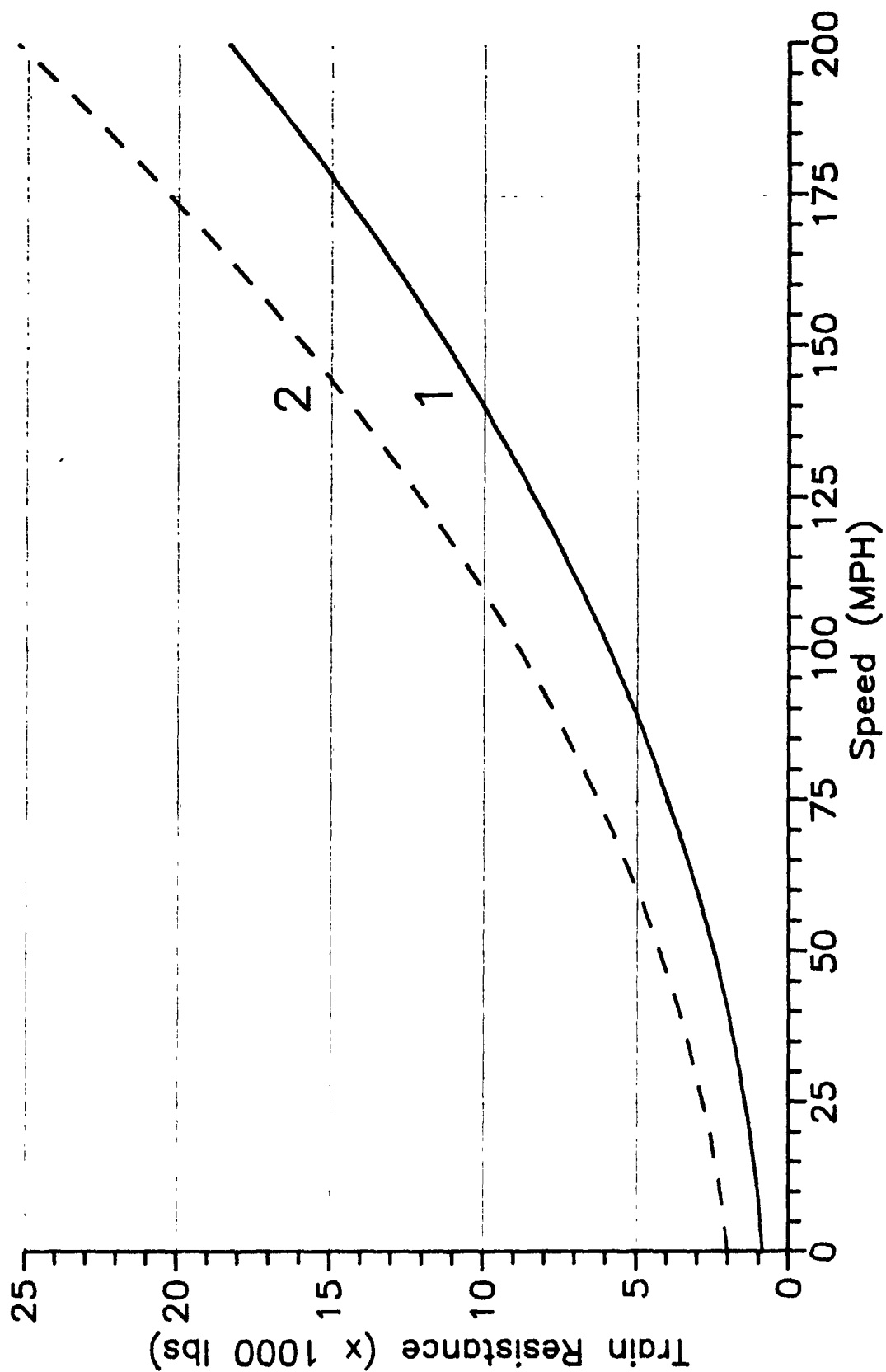
A common measure of relative power is the ratio of propulsion horsepower to total train weight, usually expressed as hp/ton. As an example, a long coal train in the flat Midwest might have 1.0 to 1.5 hp/ton assigned to it, while the faster freights (as haul-containerized merchandise) typically have about 3.0 hp/ton. The M1 freight in the examples above would be rated at 8.9 hp/ton, or between 6 and 9 times what typical freight trains currently running in the U.S. normally have assigned to them.

Conventional passenger trains commonly have a power level of about 5 to 6 hp/ton. The TGV-SE train has 17.3 hp/ton, or 3 to 3.5 times the power level of a typical conventional passenger train. More power could be added to the example trains to improve their performance, but it should be clear that power levels are already quite high.

Table 7
Trainset Data for a TGV-SE Train and Idealized Seven-Car
TGV-Style M1 Freight

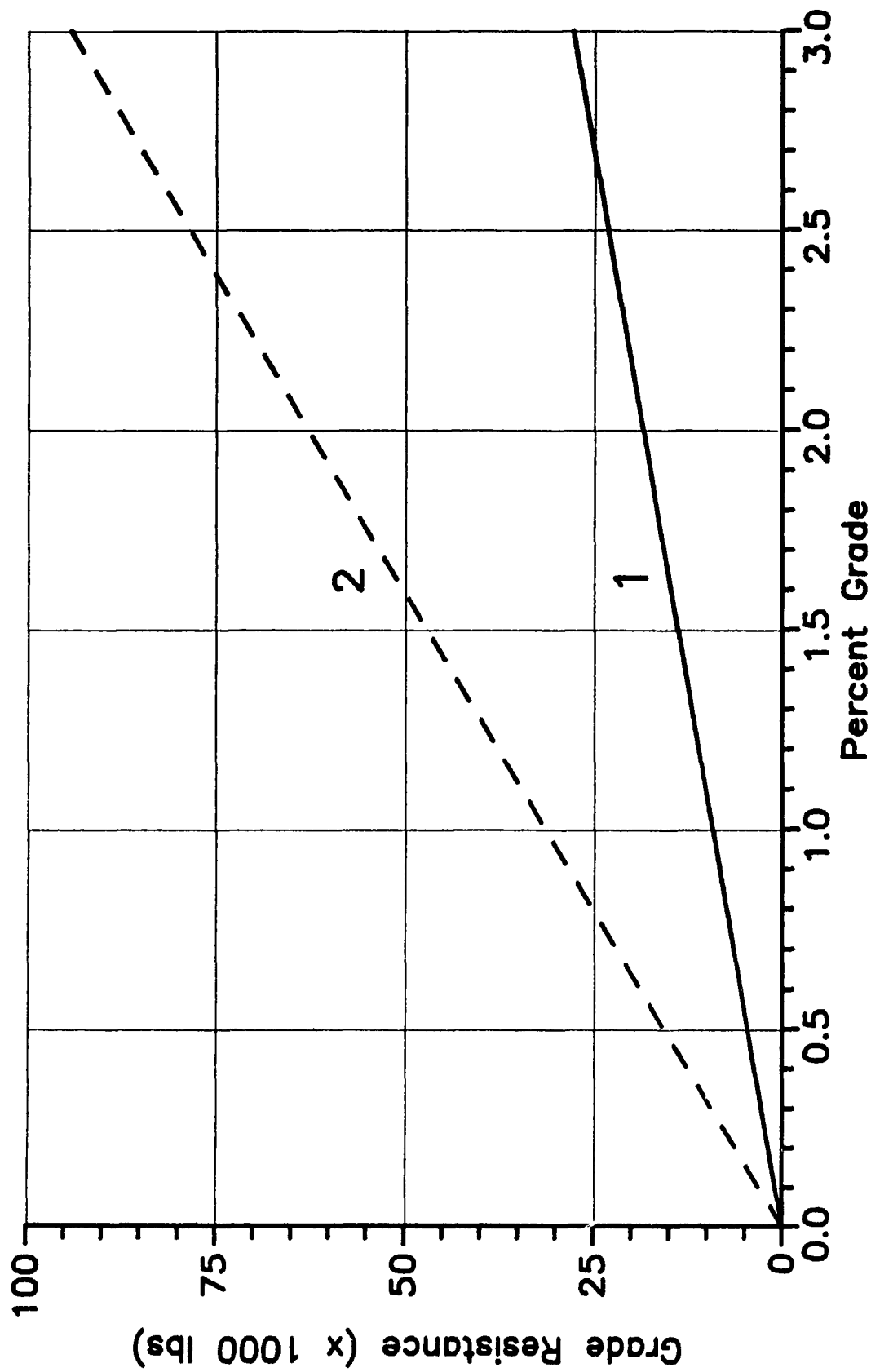
| | T G V | M1 Freight |
|--|--------------|-------------------|
| Total Train Length | 656 ft | 656 ft |
| Cross Sectional Area | 100 sq ft | 130 sq ft |
| Total Loaded Weight | 462 tons | 1,570 tons |
| Total Traction Weight | 214 tons | 360 tons |
| Weight on Each Powered Wheel | 17.8 k-lb | 30 k-lb |
| Number of Powered Axles | 12 | 12 |
| Maximum Continuous Traction Power | 8,000 hp | 14,000 hp |
| Short Time (1 Hour) Traction Power | 10,000 hp* | 17,000 hp |
| Maximum Continuous Tractive Effort | 53,000 lb* | 81,000 lb |
| Short Time (1 Hour) Tractive Effort | 94,000 lb* | 144,000 lb |

*Estimated figures for TGV-SE.



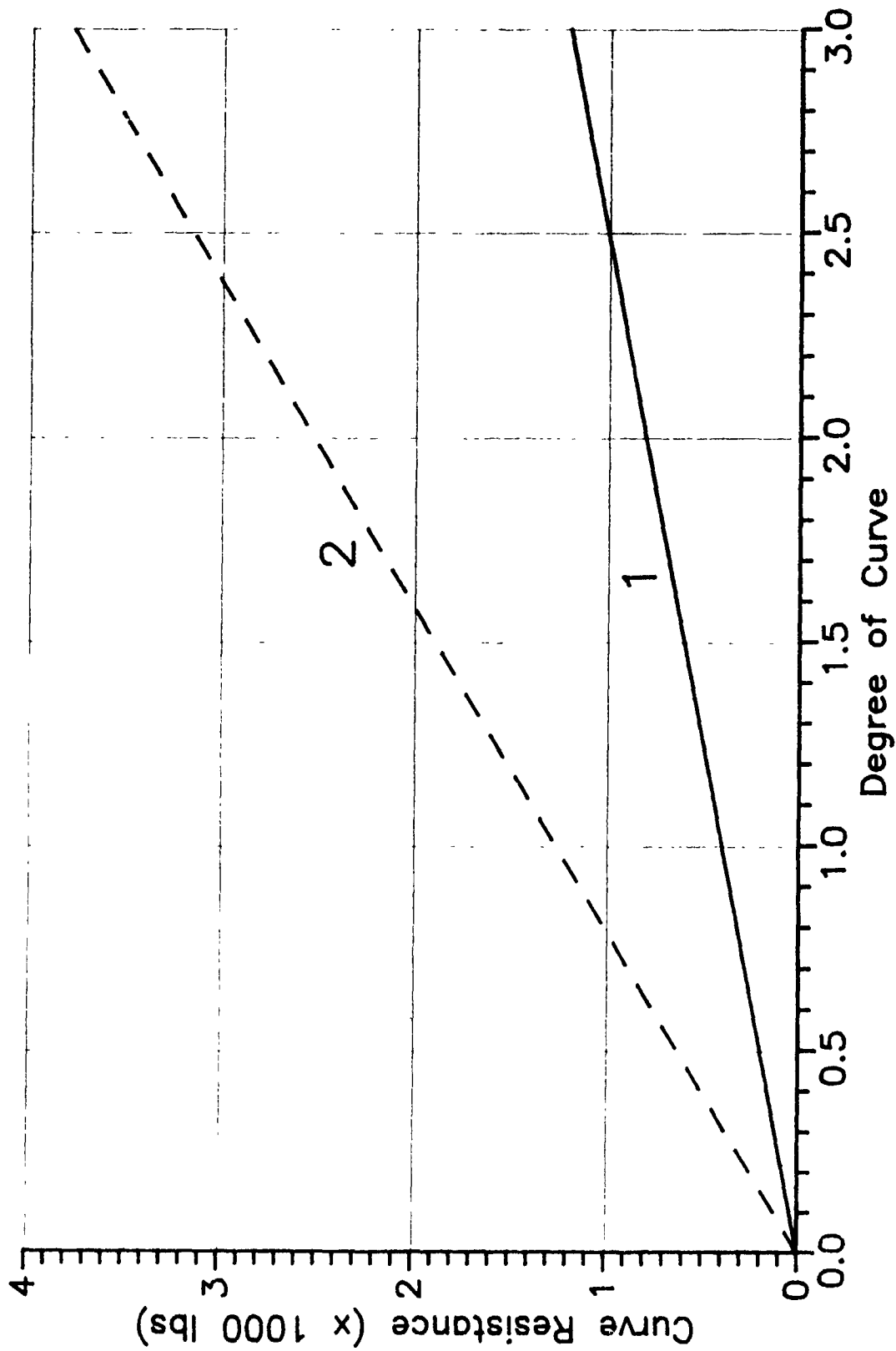
1: TGV - SE 2: Idealized 7-car TGV Freight

Figure 4. Train resistance.



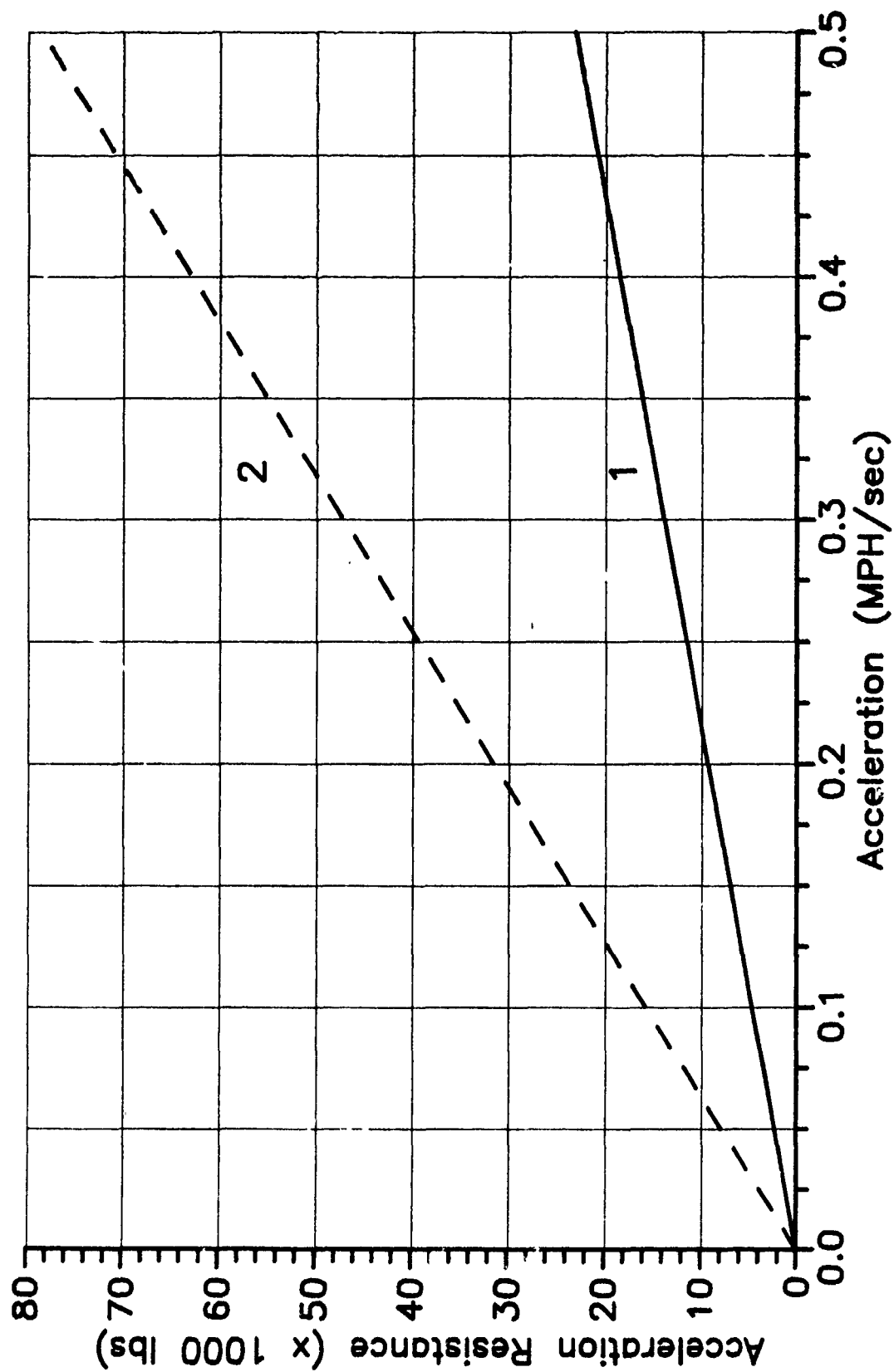
1: TGV - SE 2: Idealized 7-car TGV Freight

Figure 5. Grade resistance.



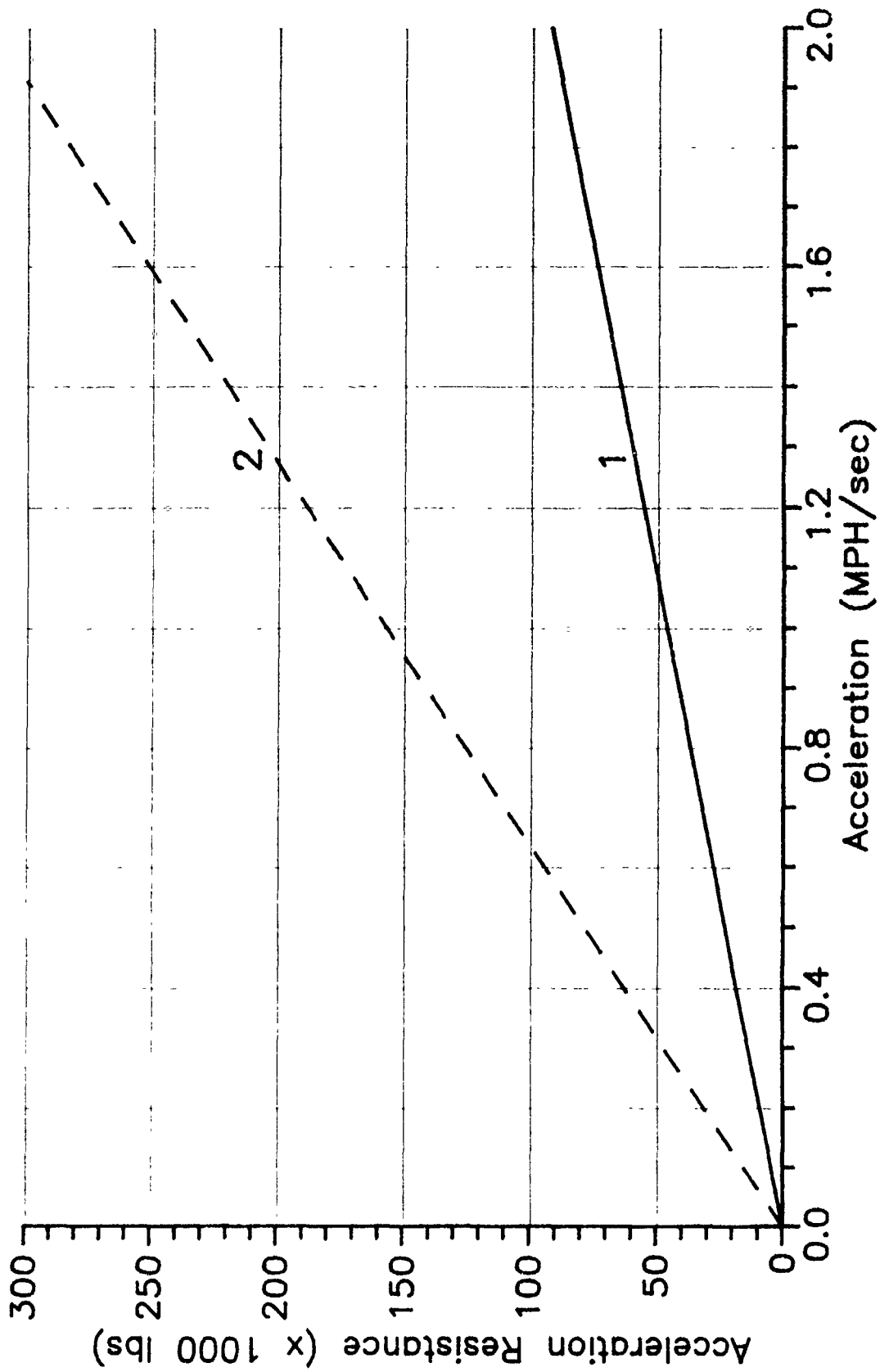
1: TGV — SE 2: Idealized 7-car TGV Freight

Figure 6. Curve resistance.



1: TGV - SE 2: Idealized 7-car TGV Freight

Figure 7. Acceleration resistance (0 - 0.5 mph/sec).



1: TGV - SE 2: Idealized 7-car TGV Freight

Figure 8. Acceleration resistance (0 - 2.0 mph/sec).

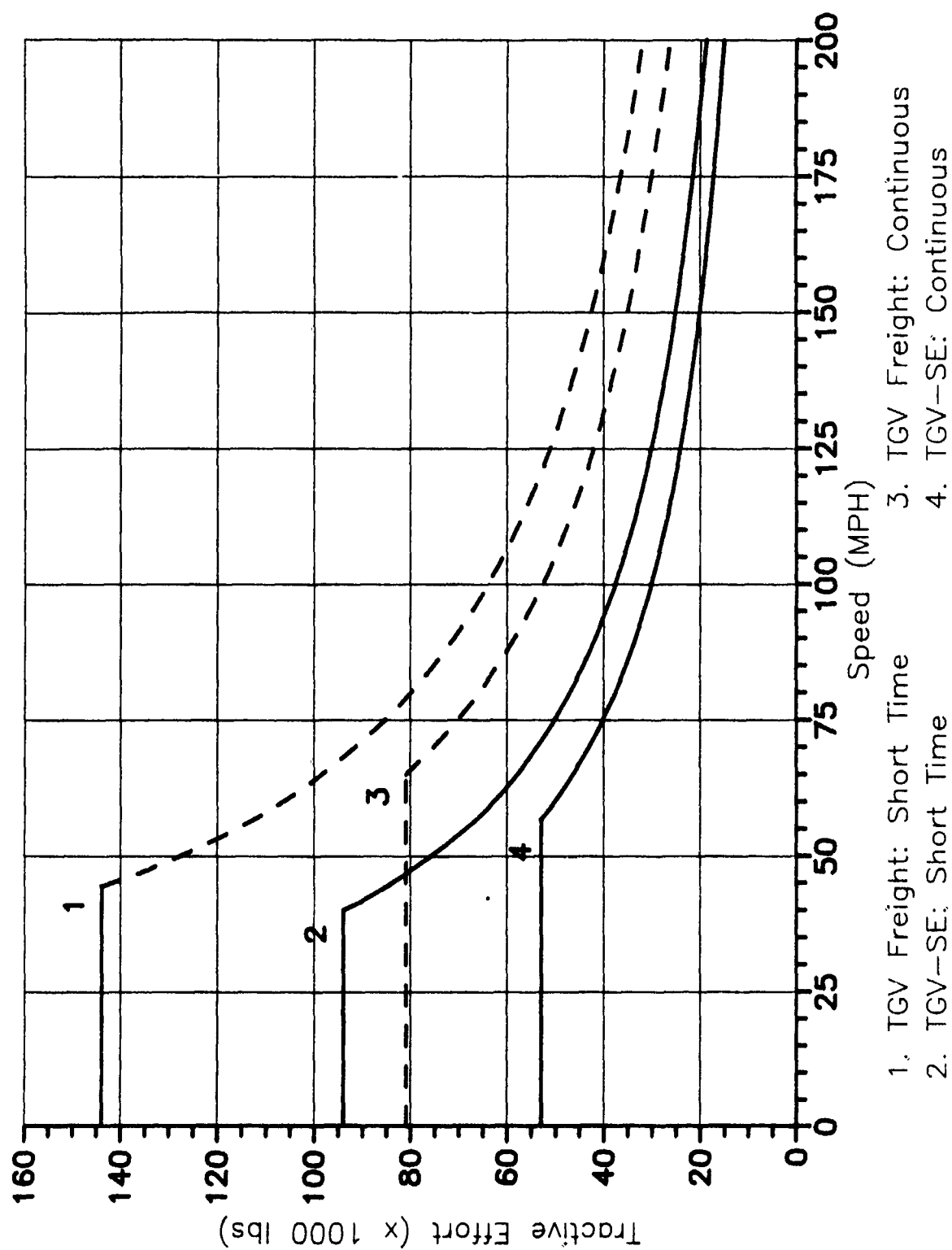


Figure 9. Tractive effort at various speeds.

Table 8
Propulsion Requirements and Capabilities (in lb) of
TGV-SE and Idealized M1 Freight at 125 mph

| | TGV-SE | Idealized M1 Freight |
|--|---------------|---------------------------------|
| 1. Force Required: | | |
| a. Level Track | 8,500 | 12,000 |
| b. Up a 1.5% Grade | 22,500 | 59,000 |
| c. 1.5% Grade and Accelerate at 0.3 mph/sec | 36,500 | 106,000 |
| 2. Tractive Effort Capability | 30,000 | 52,000 |
| 3. Traction Limit: | | |
| a. Favorable Rail Condition (9 percent) | 38,500 | 64,800 |
| b. Unfavorable Rail Condition (5 percent) | 21,400 | 36,000 |

6 MOBILIZATION REQUIREMENTS AND CONSTRAINTS

This chapter briefly examines some mobilization requirements that relate to high speed railroad transport as it currently exists. These requirements would directly affect the application of high speed trains in mobilization movements.

A National High Speed Network

For high speed trains to effectively serve during a mobilization, there must be complete routes from mobilization sites to coastal ports and other departure points: that is, there must be a national high speed railroad network designed with mobilization in mind.

One estimate of the minimum required mileage for a nationwide high speed freight railroad network might be based on the Strategic Rail Corridor Network (STRACNET), as defined by the Military Traffic Management Command. STRACNET represents a 33,000-route-mile network of railroads considered important for U.S. national defense, along with about 5000 miles of important connector lines.⁵⁴ Figures from the Association of American Railroads (AAR), which represents the Class 1 railroads—the largest carriers in the U.S.—show about 132,000 route-miles (which include about 220,000 miles of track). The American Short Line Railroad Association (ASLRA), representing the non-Class 1 roads, reports that Class 2 and 3 railroads own about 30,000 miles of track, which represents perhaps 25,000 route-miles.⁵⁵ Thus, STRACNET and its connectors comprise about 24 percent of total U.S. railroad route miles (38,000 route-miles + 157,000 route-miles).

Another method for estimating the mileage requirements for a nationwide high speed railroad network is to select routes that support substantial traffic. (It might be assumed that high speed trains would only be practical on heavy traffic lines—the more active lines of the Class 1 railroads.) A figure of 20 million gross ton-miles per year might be taken as a lower limit for heavy traffic lines. Of Class 1 railroads, about 22 percent of the track (not including yard track) qualifies.⁵⁶ This represents about 48,400 miles (220,000 miles x 0.22).

It will be further assumed that some multiple main lines and other track would not be necessary, and that much track near urban and yard areas would not be operated at high speed. With these assumptions, a basic high speed network of perhaps 40,000 miles might be achievable—a figure close to the total cited for STRACNET and its important connections.

Distribution of Cars

To avoid the slack action (or "looseness") inherent between typical individually coupled freight cars, all high speed trains are designed as semipermanently coupled "trainsets." While individual cars are generally separable, this is not usually accomplished so easily as pulling the uncoupling lever on a conventional freight car. Thus, short trainsets (which could, perhaps, be coupled together) represent the most practical configuration for high speed service.

⁵⁴ *Civil Rail Lines Important to National Defense* (MTMC, July 1986), pp 1-7.

⁵⁵ *Railroad Facts* (AAR, 1988), pp 42-43.

⁵⁶ R.A. Abbott, "Concrete Ties vs. Wood Ties: The Debate Continues," *Railway Track and Structures* (March 1989).

Since trainsets (or carsets) typically stay together as a unit, they must be dispatched that way. Likewise, if one car in a set needs maintenance or contains a defect, the whole carset will be delayed or taken out of service until repairs are complete.

Car Design and Loading/Unloading Operations

As both tractive effort and available adhesion decrease with increasing speed, effective high speed operation, even on relatively level track, depends on minimizing car weight and train resistance. As pointed out at the beginning of Chapter 3, it is unlikely that significant decreases can be made in the weight of cars intended to carry heavy equipment at high speed. Thus, the major area of potential for improved performance is in the reduction of train resistance. Attaining such reduction, however, may make loading and unloading operations far less convenient than with current designs.

Perhaps the primary (and fastest) method for loading and unloading heavy tracked vehicles such as M1 tanks is by driving the vehicles on and off the flatcars using ramps positioned at the end of railroad spurs. The alternative is to load and unload by crane. In either operation, open flatcars with decks of uniform height offer several logistical advantages. The uniform height makes driving on and off easy. The openness is also a great help in loading and unloading, especially when using a crane, and it allows good visibility and access during tiedown operations.

With respect to train resistance at high speed, the worst performers are cars with rough or uneven surfaces, discontinuous faces, and large cross-sectional areas—all of which describe M1 tanks riding on open flat cars. This conventional configuration clearly is not suited to high speed operation.

For high speed, cars require a smooth, continuous enclosure. The importance of enclosing cars is illustrated in tests conducted on the New York Central Railroad. In these tests, the enclosure of unloaded, conventional auto-carrying cars reduced *total* train resistance by 37 percent at conventional freight train speeds.⁵⁷

For comparison, refer again to the idealized seven-car TGV-style M1 freight used in the examples in Chapter 5. If conventional 140-ton flat cars are substituted for the TGV-style cars (keeping the same engines), it is estimated that train resistance would increase about 200 percent. If unfavorable rail conditions are assumed, this train could, at best, maintain 125 mph on level track with no adverse wind. There would be no reserve tractive effort to climb even a slight grade or allow for any acceleration.

Thus, for practical high speed operation, a car carrying heavy equipment must be fully enclosed with a smooth, streamlined shape. In addition, the spaces between the cars must be similarly enclosed so the whole train functions as a continuous aerodynamic unit.

The next most effective design improvement for reducing train resistance would be to reduce cross-sectional area. Perhaps the most realistic way of achieving this would be to design a depressed-center car, which could possibly reduce car height by about 2 ft and cross-sectional area by about 15 to 20 percent. Compared to the idealized M1 freight, it is estimated that at 125 mph, the use of a depressed-center car design would reduce train resistance by an additional 10 to 15 percent. This option, however,

⁵⁷ William W. Hay, p. 79

would probably eliminate the possibility of circus-style loading and unloading, in which the tanks are driven up ramps and onto the flatcars.

Another design issue that would affect loading and unloading operations is the common use of semipermanently coupled carsets in high speed service (to eliminate slack action). With cars configured in this manner, many loading spurs, wyes, passing sidings, storage tracks, repair tracks, etc., would probably need lengthening, or even realignment, to accommodate multiple carsets.

As indicated in Chapter 3, dynamic wheel loads are also of concern at higher speeds. If heavy freight is to be run at 125 mph, it is not likely that the current 33-ton axle loads would be permitted; the track deterioration rate would be extremely high. Carrying M1 tanks at this speed would probably require each tank to be carried in a separate four-axle car, perhaps in articulated sets with steering trucks. This arrangement would reduce axle loads to a more acceptable level of about 23 tons.

7 ASSESSING THE COSTS AND BENEFITS OF HIGH SPEED

Upgrading Existing Lines

Before considering the construction of new high speed lines, the feasibility of upgrading existing lines should be examined. The use of existing lines requires, first, that the routes be suitable for high speed service. Using the basic 40,000-mile network suggested in Chapter 6, the amount of suitable existing mileage was assessed.

From Table 5, it is clear that high speed operations are practical on curvature of, at most, about 1 degree. Table 9 lists the approximate amount of track on Class 1 railroads with various degrees of curvature. This table indicates that about 20.6 percent of Class 1 track is in curves sharper than 1 degree. If it is allowed that heavy traffic lines have somewhat less curvature than average, it might be estimated that about 15 percent of the 40,000-mile high speed freight network would contain track with curvature sharper than 1 degree. If this were the case, then 6000 miles ($0.15 \times 40,000$ miles) of the network would be unsuitable for high speed operation due to its high curvature.

In practice, the percentage of track with speed restrictions due to curvature would be higher than the stated 15 percent, allowing for tangents before and after curves on which the trains would have to slow down or speed up. In addition, there would be many tangents between curves too short for acceleration to high speed. Thus, perhaps 25 percent (10,000 miles) of the high speed system would be likely to have speed restrictions due to curvature.

Certainly, much curved track within the assumed 40,000-mile high speed freight network would be located in passes through the Appalachian, Rocky, Sierra, and Cascade mountain chains, and in other areas where any significant realignment would be extremely expensive, even if the necessary land was available.

If high speed freight trains were similar to the idealized example in Chapter 5, then the steepest grade on which high speed (125 mph) could be maintained (allowing for unfavorable rail conditions) is about 0.8 percent. While no specific figures are presented here for the percentage of track with grades steeper than 0.8 percent, the figure would clearly be quite substantial, especially in hilly and mountainous areas.

Thus, even from these simple assessments, it appears that a high percentage of existing route mileage in the U.S. would not be suitable for high speed trains. A quick examination of systems in operation elsewhere in the world also indicates that practical application of high speed often requires new construction. The Japanese Tokaido and Sanyo bullet train lines and the French TGV-SE and Atlantic lines are all new construction. In addition, 267 miles of new lines are currently under construction in Germany to accommodate the high speed service scheduled to begin operation in 1991.⁵⁸

⁵⁸ T. Rahn and W. Spohrer.

Table 9
Estimated Mileage of Class I Track in Curves

| Degree of Curvature | | Percent of Track | | Track Mileage | |
|---------------------|--------------------|------------------|------------|---------------|------------|
| Greater Than | Less Than or Equal | % | Cumulative | Miles | Cumulative |
| 7 | --- | 1.6 | 1.6 | 3,520 | 3,520 |
| 6 | 7 | 0.7 | 2.3 | 1,540 | 5,060 |
| 5 | 6 | 1.8 | 4.1 | 3,960 | 9,020 |
| 4 | 5 | 1.9 | 6.0 | 4,180 | 13,200 |
| 3 | 4 | 3.8 | 9.8 | 8,360 | 21,560 |
| 2 | 3 | 5.0 | 14.8 | 11,000 | 32,560 |
| 1 | 2 | 5.8 | 20.6 | 12,760 | 45,320 |
| 0 | 1 | 4.8 | 25.4 | 10,560 | 55,880 |

*Source: R.A. Abbott.

The Cost of New Construction

In a study conducted for the State of Pennsylvania, the costs for a double track, high speed route from Philadelphia to Pittsburgh (315 miles) were estimated (in 1986 dollars). The selected route included both existing mileage and new construction. For track, roadway, and earthwork only, costs ranged from \$5 million to \$25 million per mile.⁵⁹ A 36-mile segment of new route between Altoona and State College averaged \$12.5 million per mile. The study also reported that costs for construction of the complete system (including electrification, signals, communications, etc.) averaged \$22.8 million per mile over the whole route. These costs were noted as being higher than the expected national average due to Pennsylvania's relatively rough terrain.

⁵⁹ Robert E. Schmelz, "HSR Cost Estimating Techniques in Pennsylvania," *ASCE Journal of Transportation Engineering*, Vol 115, No. 1 (January 1989).

The effect of terrain is also evident in the construction costs and estimates for German high speed lines. The new 203-mile line between Hanover and Wurzberg has 39 percent of its track in tunnels, and at a conversion rate of \$1 U.S. = 1.72 DM, the line's average cost per mile is about \$30 million. The cost of the proposed high speed line from Hanover to Berlin, which is said to run through relatively flat country and require no tunnels, is estimated at about \$9.3 million per mile.⁶⁰

System costs for building the French high speed lines are reported at \$7.2 million per mile for the new Atlantic line and \$6.3 million per mile for the Southeast line, which began operation in 1981.⁶¹ Estimates prepared for proposed TGV-style high speed lines in Florida give an average cost of \$7 million per mile, which is said to be low due to the state's flat terrain.⁶² Allowing an average cost of \$12 million per mile, the example 40,000 mile U.S. high speed railroad network would cost \$480,000,000,000—without trains, stations, terminals, or equipment servicing facilities.

Operating Costs and Energy Consumption

System operating costs will, of course, vary with the level of service provided, with a primary variable being the number of trains run. Due to the large difference in type of service, cost estimates for high speed freight operation cannot be easily made from comparisons with existing high speed passenger operations.

However, for one significant category, comparative figures are relevant: energy consumption. For the years 1984 through 1986, electric energy consumption accounted for about 38 percent of all direct operating expenses (including administration, but not equipment maintenance) on the French TGV-SE line.⁶³

It is generally accepted that the required propulsive energy is nearly proportional to the square of operating speed. Figure 10 shows estimated energy consumption for a EMU Metroliner train operating between New York and Washington at varying maximum speeds. As the route and operations were known in detail, energy calculations included allowances for stops and sections where speeds would be restricted, such as through the Baltimore and New York tunnels, near terminals, curves, etc. This results in total energy consumption being roughly proportional to the *maximum* speed to the power of 1.5.

Maintenance Costs

As the section *Dynamic Loads and Wheel/Rail Impacts* in Chapter 3 has already implied, track maintenance costs increase as operating speed increases. These increases are related to the more exacting track geometry requirements for high speed operation and to the greater deteriorating effects of dynamic loads at higher speeds.⁶⁴

⁶⁰ Gerhard Pintag, "Capital Cost and Operations of High-Speed Rail System in West Germany," *ASCE Journal of Transportation Engineering*, Vol 115, No. 1 (January 1989).

⁶¹ Robert E. Schmelz, p 93.

⁶² L.D. Shen and A. Farooqi, p 14.

⁶³ Nicholas M. Brand and M. Lucas, "Operating and Maintenance Costs of the TGV High-Speed Rail System," *ASCE Journal of Transportation Engineering*, Vol 115, No. 1 (January 1989).

⁶⁴ Andre Prud'Homme, "Track Problems Posed by the Running of High Speed Trains," *French Railway Techniques*, Vol 21, No. 1 (1978).

A rough idea of the increased maintenance cost due to higher speed can be obtained by examining expenses on the French TGV-SE line. In 1985, the TGV required about \$11,000 per mile for track maintenance⁶⁵ while about \$7000 to \$8000 was required for maintaining a mile of track on a moderate-to-heavy traffic U.S. line. While it may be argued that at least part of the higher French maintenance costs might be attributable to public railroad ownership vs. private ownership in the United States, it should also be noted that the SNCF (French National Railways) received no government assistance in building the TGV line. The money for construction and the purchase of trainsets was supplied by SNCF and the bank loans they obtained. Likewise, SNCF is solely responsible for paying off those loans.⁶⁶

As noted earlier, practical high speed operation requires electrification, which in turn requires the construction and maintenance of a catenary system to supply power to the trains. In an estimate made for a TGV-style operation in the U.S., catenary maintenance was given as \$3300 per mile (in 1987 dollars).⁶⁷

If heavy freight is to be carried at high speed, another important effect on track maintenance must be considered—an increase in wheel loads. As no high speed freight operations currently operate, no figures are available for track maintenance expense increases from the combination of high speed and heavier loading. However, many years of experience with increasing wheel loads, especially in the U.S. and Canada, have clearly shown that increased wheel loading significantly increases track maintenance expenses.

An estimate of the wheel load effect can be made using information from a study by the Illinois Central Gulf Railroad on the relationship between wheel loads and track maintenance costs. While the specific figures are for conventional wood tie track, the indicated trend would probably apply to a variety of track types. Referring again to the two trains from the examples in Chapter 5, the study results show about a 35 percent increase in total track maintenance cost due to increasing wheel loads from the level of the TGV-SE (18,700 lb) to that for the idealized M1 freight (30,000 lb).⁶⁸

Benefits: The Value of High Speed

As the literature on high speed railroad service indicates no significant operating, maintenance, energy consumption, or ecological advantages over conventional service, the dominant benefit of these operations appears to be in the speed itself, or in the time saved through higher speed travel. Thus, the net benefit would be obtained by comparing the value of the time saved to the costs of establishing, operating, and maintaining a high speed railroad network.

It would appear necessary to address the following kinds of questions in assessing the value of high speed service in mobilization activities:

1. What percentage of total transportation time, from origin to end, does movement by railroad currently account for?

⁶⁵ Jean-Pierre Pronost, p 396.

⁶⁶ A. DeTessieres, p 390.

⁶⁷ Nicholas M. Brand and M. Lucas, p 46.

⁶⁸ Robert E. Ahlf, *Heavy Four-Axle Cars and Their Maintenance of Way Costs*, unpublished study (Illinois Central Gulf Railroad, undated).

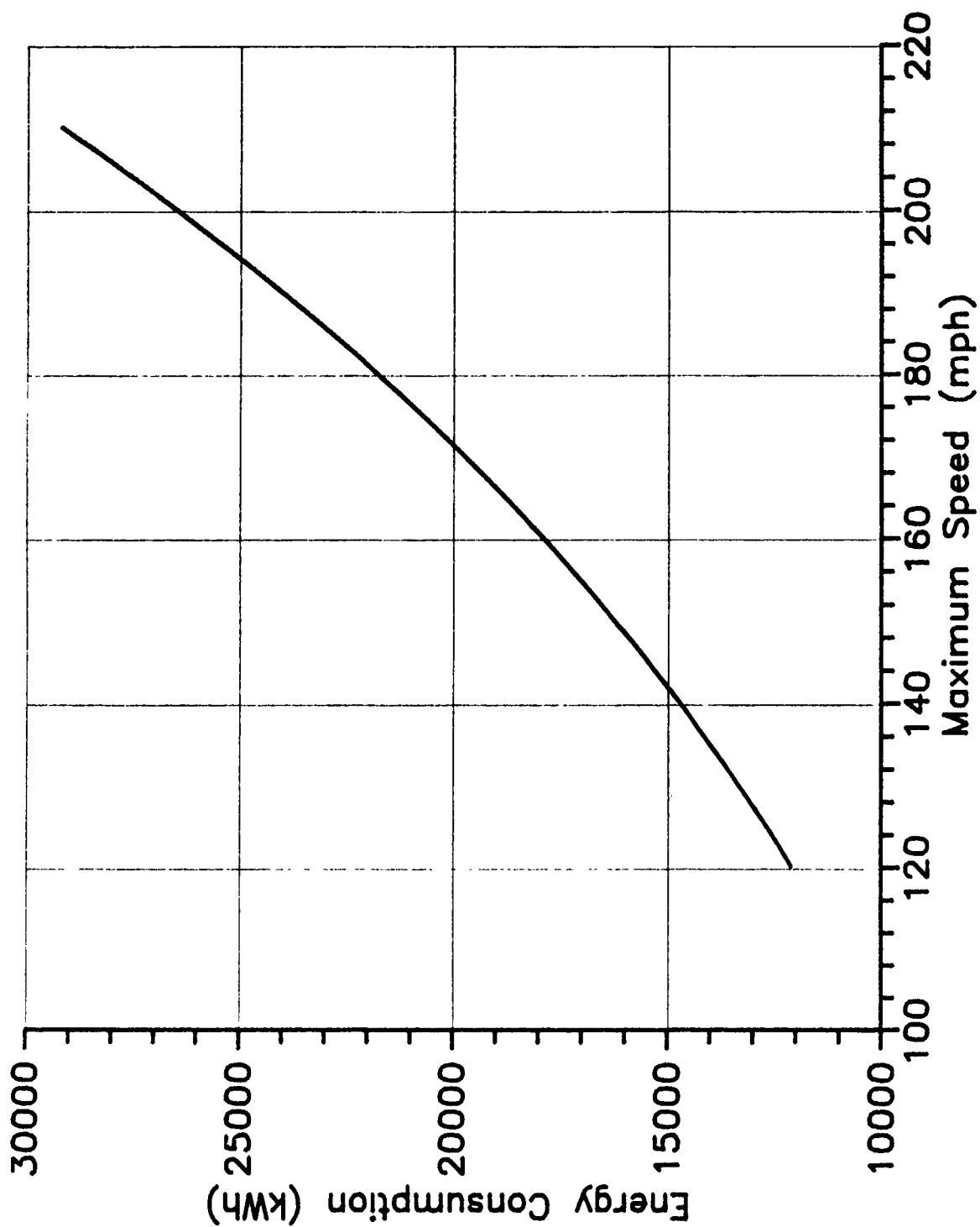


Figure 10. Estimated energy consumption for an EMU Metroliner-type train between New York and Washington. (Source: Louis T. Klauder, Jr., "Engineering Options for the Northeast Corridor," *Transportation Research Record*, No. 1023 [Transportation Research Board, 1985], p 3.)

2. Including loading and unloading, how much time might actually be saved if a high speed railroad network were in place?

3. Would the time savings speed up the total mobilization effort, and if so, by how much?

4. Could significant improvements be made in the way the existing railroad system is being used?

5. How should an amount of time saved during mobilization relate to an acceptable expense for the time savings?

Such questions, however, are beyond the scope of the present study.

8 CONCLUSIONS

This report has identified key issues pertaining to the application of existing conventional high speed railroad technology to support Army mobilization. These issues are related to the characteristics of existing high speed systems, the technological demands implicit in using high speed railroads for mobilization, route alignment and track requirements, system performance, and potential benefits versus costs.

As mobilization plans currently appear, the use of railroad transport implies the need to haul freight—especially heavy tracked equipment. It is important to restate that there are currently no high speed heavy freight railroad lines in operation anywhere in the world. Neither are there indications of any such operations being planned for the near future.

The primary conclusion of this work is that high speed heavy freight operations present technical challenges of an order of magnitude beyond those for high speed passenger operations. Existing high speed trains (and those soon to be in service) appear to be approaching the practical limits of conventional steel wheel-on-steel rail technology. The hauling of heavy freight at high speed would push much closer to these limits, if not exceed them.

The full potential of a high speed operation in reducing trip times is gained only when trains can run at (or near) their maximum speed over a high percentage of the route. As both grades and curvature would be severely restricted for high speed freight service, these operations would be practical only on completely new routes, built to very high standards and maintained within very tight tolerances.

Since effective operation of high speed trains requires straight electric propulsion, with electricity supplied through overhead wires, high speed lines would have to include a catenary and electric power distribution system.

For significant reduction in trip times, high speed routes must connect installations with their U. S. mobilization destinations, which means the establishment of a national high speed network. At current estimates this network might have an average cost of about \$12 million per mile, not including the cost of trains, stations, terminals, or equipment-servicing facilities.

To permit a successful high speed freight operation, locomotives would require much higher horsepower than in existing units. Even then, trains would be quite short compared to conventional freight trains. Also, like the high speed passenger trains now in service, high speed freight locomotives and cars would require advanced braking and suspension systems, as well as fully enclosed aerodynamic shaping to keep air resistance within practical limits, a requirement that could affect how equipment could be loaded and unloaded.

Any assessment of the net benefits of a high speed railroad operation must be made with an understanding of the magnitude of cost and technological challenge inherent in the construction, operation, and maintenance of these systems.

METRIC CONVERSION TABLE

| | | |
|--------------|---|-------------------|
| 1 in. | = | 2.54 cm |
| 1 in. | = | 25.4 mm |
| 1 mile | = | 1.609 kilometers |
| 1 lb (force) | = | 4.45 newtons |
| 1 lb (mass) | = | 454 grams |
| 1 hp | = | 746 watts |
| 1 hp | = | 0.746 kilowatts |
| 1 ton | = | 0.893 metric tons |
| 1 ton | = | 908 kilograms |

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ABBREVIATIONS

| | |
|-----------------|---|
| AAR | American Association of Railroads |
| APT | Advanced Passenger Train |
| AREA | American Railway Engineering Association |
| ASCE | American Society of Civil Engineers |
| ASLRA | American Short Line Railroad Association |
| FRA | Federal Railroad Administration |
| HST | High-Speed Train |
| ITE | Institute of Transportation Engineers |
| LRC | Light-Rapid-Comfortable |
| MTMC | Military Traffic Management Command |
| SNCF | French National Railways |
| STRACNET | Strategic Rail Corridor Network |
| TGV | Train à Grande Vitesse |
| TGV-SE | TGV, Southeast line |

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